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WATER QUALITY OF THE COLORADO RIVER SYSTEM: HISTORICAL TRENDS IN CONCENTRATION, LOAD, AND MASS FRACTION OF INORGANIC SOLUTES

January 1984

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16. ABSTRACT

Systematic changes in salt loading may be responsible for recent decreases in the salinity in the lower Colorado River Basin. A systematic change might manifest itself as a long-term shift in the concentration, load, or mass fraction of major solutes. In this study, shifts were identified using trend analyses and by comparison of mean values before and after major reservoir development. Representative monthly solute concentration and streamflow values were computed for 15 major gage stations. For the 12 stations with sufficient data prior to major flow regulation, trends were identified using regression models. Significant decreases were found for magnesium, sodium, and sulfate at nine stations, accounting for an overall reduction of 2 mg/L per year for the Lake Mead inflow during the months from December to March. After construction of the Colorado River Storage Project reservoirs, the seasonal variability in salinity was reduced at all downstream stations; concentrations generally decreased in May and June, and increased during the August-March season. Few trends were evident after flow regulation. In addition to reservoir construction, several activities of man were hypothesized as causes of identified trends and mean value changes. However, the major reservoirs, Lakes Powell and Mead, masked the effects of all other activities. No significant trends in load were found for the station below Lake Mead after 1965.

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January 1984

Colorado River Project

Applied Sciences Branch
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SUMMARY

This report presents the results of a study initiated by the Colorado River Water Quality Office of the USBR (Bureau of Reclamation) to identify possible systematic changes in salt loading to the Colorado River and its major tributaries. A systematic change may involve long-term alterations of natural sources of salt or the impact of human activities on salt loading or salt transport in the river. Systematic changes have been suggested as a possible cause of the recent decreases in the salt concentration at Imperial Dam in the Lower Basin. Reducing the salt load in the river is the goal of the Colorado River Water Quality Improvement Program. If systematic changes in the salt loading characteristics of the basin have occurred, they must be considered in formulating plans to achieve salinity reduction.

A systematic change might manifest itself as a long-term shift in the concentration, load (absolute mass), or mass fraction (relative mass) of one or more of the major solutes in the system. Probable shifts can be identified using trend analysis or by comparison of mean values before and after major alterations within the basin. Both approaches were used in this study. Regression techniques were employed to test for significant trends and Student's *t* test was used to assess the mean value changes. Six major ions were selected for analysis: calcium, magnesium, sodium, chloride, sulfate, and bicarbonate. Together these account for more than 95 percent of the total solute load at the major gage sites in the basin. Fifteen sites, representing the major divisions of the basin, were studied. Data for these sites were obtained from the USGS (U.S. Geological Survey) computerized water data base, WATSTORE.

To isolate potential sources of significant trends or mean value changes, these changes must be traceable from downstream to upstream gage sites. Therefore, consistent data sets were required for all stations. The first step in the study was to create a data file of representative monthly average streamflow and solute concentration values for the selected gage sites. These computer data files are being maintained for future research on the Colorado River system.

The data generated was first used to test various methods relating solute concentration to streamflow. This was necessary so changes in concentration caused by natural flow variations could be accounted for in subsequent regression analyses. A theoretical residence time model was compared with the widely used empirical power model. The two models produced equally good predictions for periods prior to flow regulation. These models are available for updating input data used in the USBR Colorado River Simulation System models.

Although 15 gage sites were selected, trend analyses were completed for only the 12 sites that had adequate records of water quality prior to major flow regulation. Several different regression models were used, and their results were generally corroborative. Significant negative (decreasing) trends were found for magnesium, sodium, and sulfate at approximately 75 percent of the sites. At the Lees Ferry and Grand Canyon gage sites, concentrations of these three ions declined in proportion to their electrical charge and relative mass, resulting in a reduction in TDS (total dissolved solids) of approximately 2 mg/L per year for the low flow period, December–March, from 1926 to 1961.

After construction of the Colorado River Storage Project reservoirs in the early 1960's, the variability of both solute concentrations and mass fractions was reduced at downstream gaging stations. This reduction was generally proportional to the degree of regulation. At some sites, trends toward further reduction in variability developed after initial reservoir filling. Several other activities of man, including mining, urbanization, and salinity control practices, may have affected water quality in the basin during this period. Impacts decreased with distance downstream, but were often identified at more than one gaging station. However, the major reservoirs, Lakes Powell and Mead, concealed all impacts that had occurred in the Upper Basin.

No significant trends in the load for any solute have been identified for the station below Hoover Dam since 1965; however, the concentration of all solutes except chloride decreased there during at least one season.

Additional research is recommended to determine the possibility and probable magnitude of continuing impacts of major reservoirs on downstream salinity. Also, because of the relative chemical stability at the gage site below Hoover Dam, the changes observed downstream at Imperial Dam may have resulted from changing conditions in the Lower Basin area. Therefore, an extension of the present study, with additional Lower Basin gage sites included, is recommended. This extension should also update the monthly data base and data base generation procedures, and limit statistical analyses to those recommended in the present work.

INTRODUCTION

Description of the Basin

The Colorado River Basin includes 632 000 km^2 in the Western United States and northern Mexico (fig. 1). The average unregulated flow of the Colorado River below Lees Ferry, Arizona, is 16.0–18.5 km^3/a, which is small compared with that of other North American rivers with similar size basins. However, the river is an important source of water for more than 12 million people and approximately 1 million ha of irrigated agricultural land [1].*

The headwaters of the Colorado and its major tributaries, the Green and San Juan Rivers, lie in the high peaks of the Rocky Mountains, where the annual precipitation is normally between 100 and 150 cm. Most of its course, however, crosses the semiarid Colorado Plateau and the Sonoran Desert, where the average annual precipitation is only 6 cm [2]. Many of the geologic formations in this part of the basin are of marine origin and contain sodium chloride (halite) and calcium sulfate (gypsum) salts. Natural springs and man-made wells intercept saline ground waters associated with these formations and discharge into the river system. Soils in much of the basin have developed residually on gypsum-bearing shales. Irrigation water applied to this land promotes weathering and dissolution of salts from the soil and underlying shales. As a result this water returns to the river with a greater salt load than was diverted [3]. Irrigation also increases dissolved mineral concentrations in the river by depleting the streamflow volume. As a result, TDS (total dissolved solids) increases from approximately 50 mg/L at the headwaters to 800 mg/L (1977-1981 average) [2] at Imperial Dam, the final diversion point on the Colorado River in the United States.

Water resource development in the basin began when the pioneers settled there in the 1860's. By the 1920's, when the USGS (U.S. Geological Survey) began monitoring surface water quality, much of the present irrigation development was already in place, and several reservoirs and transbasin diversions had been constructed in the upper reaches of the basin. The first major multipurpose reservoir, Lake Mead, began filling in 1935. Development in the basin upstream of Lake Mead continued gradually, though mainstem flow was essentially unregulated until the early 1960's. Between 1962 and 1966, the storage capacity above Lees Ferry increased from 3 to 45 km^3, mostly as a result of the construction of the Colorado River Storage Project reservoirs: Navajo Reservoir on the San Juan River (began filling in November 1962), Blue Mesa Reservoir on the Gunnison River (November 1965), and Lake Powell on the Colorado River (March 1963). Reservoir and transbasin diversion development in the basin upstream of Lake Mead is outlined in table 1 of appendixes B through P.

Colorado River Water Quality Improvement Program

During the period of accelerated development, the USGS initiated an appraisal of the water supply in the basin [3]. Its purpose was to determine whether development would be limited by "legal, physical, and economic factors." Much of the study focused on the impacts of human activities on salinity. It concluded that, by 1957, approximately half the average annual TDS concentration at Lees Ferry was caused by domestic, industrial, and agricultural activities within the basin and transbasin diversions.

By 1970, salinity in the lower Colorado River was recognized as a basinwide problem [4]. TDS standards for lower basin gage locations were adopted by the basin States in response to amendments to the Federal Water Pollution Control Act of 1972. These standards were set at the 1972 average concentrations, thus establishing a policy of nondegradation. To offset the effects of future water development, the Colorado River Basin Salinity Control Act of 1974 authorized the USBR to construct 4 salinity control projects and investigate the feasibility of constructing 12 others. The location of active projects upstream of Hoover Dam is shown in figure 1.

At the same time, computational methods were developed to predict the effects of planned water resources development. Early projections indicated that salinity increases observed at Imperial Dam between 1949 and 1970 would continue, with TDS concentration eventually reaching 1200 mg/L [4, 5, 6]. However, contrary to these projections, salinity has actually decreased since 1970 (see fig. 2).

It is not clear whether this decrease in salinity is part of a long-term cycle or is indicative of a permanent change somewhere in the system. Other investigators [7, 8] have argued that new conditions created by impoundment of large reservoirs have permanently altered chemical processes in the river system and may be a factor

* Numbers in brackets refer to entries in the bibliography.

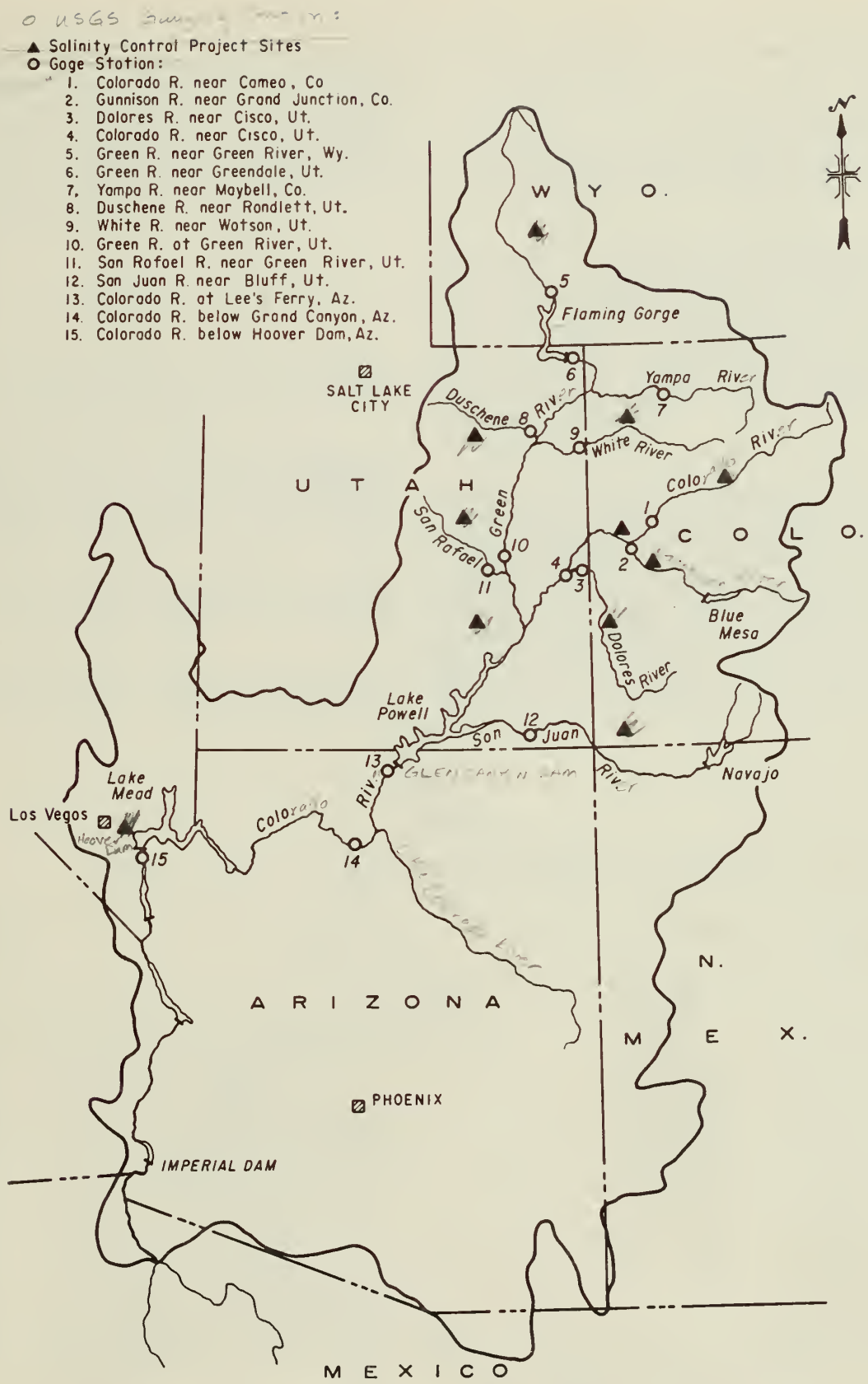

Figure 1. — Map of salinity control project sites and gage stations in the Colorado River Basin.

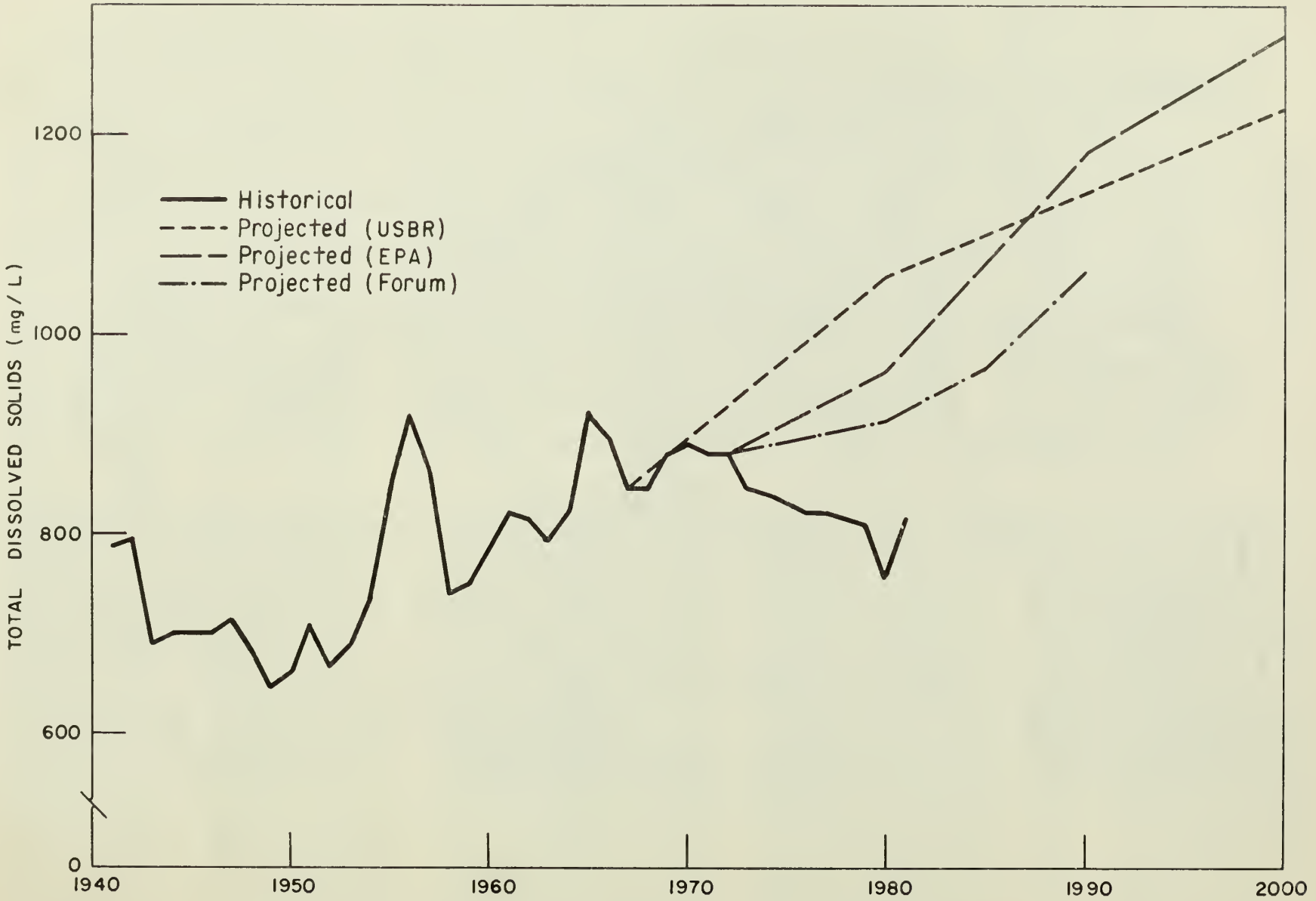

Figure 2. — Historical vs. projected TDS at Imperial Dam (without salinity control).

in decreasing salinity. Other possible factors are manmade or natural alterations in the salt load producing areas of the basin. At a given point in the system, a systematic change might manifest itself as a shift in the solute concentration-streamflow relationship or in the absolute or relative solute load.

Research Objectives

As a first step in evaluating the possibility of a systematic change, the present study was initiated with the following objectives:

1. Create a data base that includes average monthly streamflows and major solute concentrations at selected gaging stations in the Colorado River Basin

2. Develop a theoretical model for the relationship between streamflow and individual solute concentrations

3. Identify significant long-term trends in solute concentration, load, and mass fraction for the period before the construction of major upstream dams

4. Identify significant changes in the solute concentration, load, and mass fraction after the accelerated reservoir development of the early 1960's

Fifteen stations were selected for analysis (table 1). These are all principal stations used to define concentration-streamflow relationships in the USBR's Colorado River Simulation System. Except for the station on the Duchesne River and those below Lake Mead and Flaming Gorge Reservoir, all had adequate water quality records for the planned statistical analyses.

This report describes the procedures used to develop the data base and presents the results of the statistical analyses. It includes an evaluation of the selected statistical procedures based on the ease of interpreting their results. A cursory interpretation of the results and their implications for the salinity control program is also given, though a more complete analysis is recommended. No attempt is made to reconcile the recently observed TDS at Imperial Dam with earlier projections.

Table 1. — *Colorado River Basin gaging stations selected for analysis*

USGS number	Location	Period of record[1]
90955	Colorado River near Cameo, Colorado	12/33- 6/79
91525	Gunnison River near Grand Junction, Colorado	10/31- 8/82
91800	Dolores River near Cisco, Utah	5/51- 9/82
91805	Colorado River near Cisco, Utah	10/28- 4/83
92170	Green River near Green River, Wyoming	10/51- 5/82
92345	Green River near Greendale, Utah	10/56- 6/83
92510	Yampa River near Maybell, Colorado	12/50- 8/82
93020	Duchesne River near Randlett, Utah	1/51- 3/83
93065	White River near Watson, Utah	12/50- 7/79
93150	Green River at Green River, Utah	8/28- 4/83
93285	San Rafael River near Green River, Utah	2/47- 5/83
93795	San Juan River near Bluff, Utah	5/29-10/81
93800	Colorado River at Lees Ferry, Arizona	5/27- 6/82
94025	Colorado River near Grand Canyon, Arizona	11/25- 3/74
94215	Colorado River below Hoover Dam, Arizona	10/40- 4/83

[1] Includes all data necessary for generation of monthly concentrations as described in this report.

DATA BASE DEVELOPMENT

A series of computer procedures was developed to generate representative monthly values from existing data. These procedures were also used to check for errors in the data base and to estimate missing values. A complete guide to the use of the component programs is given in appendix A.

WATSTORE Retrieval

All data used in this project were retrieved directly from the USGS WATSTORE data base by an automatic communication link between the USBR CYBER and USGS IBM computers. These data include mean daily streamflows, daily specific conductances, and periodic chemical analyses of the following: calcium, magnesium, sodium, chloride, sulfate, bicarbonate, alkalinity, TDS (residue on evaporation at 180 °C), and specific conductance. Chemical analyses are reported for time-weighted composite samples until September 1969 and for monthly discrete samples thereafter.

Initial Analysis

Potential errors in the periodic chemical data were identified by testing the differences between the observed and predicted values of: (1) total solute concentration, for which the predicted value was the sum of constituents and the observed value was the residue on evaporation (increased to account for lost bicarbonate); (2) specific conductance, for which the predicted value was computed from equivalent ionic conductances; and (3) net charge, for which the predicted value was assumed to be zero. Obvious errors were checked and corrected, as described in appendix A.

Possible errors in daily values were identified from outliers in the log-log regression of conductance on streamflow. Typographical errors in the WATSTORE data were confirmed and corrected by comparing them with values in USGS Water Supply Papers. Other obviously erroneous values were set to zero and treated as missing values in subsequent procedures. Changes made to WATSTORE data are documented in table 2 of appendixes B through P.

Single missing solute concentrations in individual chemical analyses were estimated assuming a net charge of zero. When two or more values were missing from an analysis, no estimates were attempted; but the sum of six ions, necessary to compute mass fraction, was estimated from regression on evaporation residue TDS. The periodic chemical analyses, including missing value estimates, were then combined with daily values of streamflow and conductance to estimate solute concentrations for days samples were not taken.

Generation of Monthly Mean Values

Composite sample analyses were assigned to each day of the composite period; discrete sample analyses were assigned to the day of collection. Substitutions for missing daily values were generated by interpolation in a hierarchical process in which streamflow was estimated first, followed by conductance, and finally solute concentrations. This sequence was employed because streamflow was used to weight the interpolation of conductance, and conductance, in turn, was used to weight the interpolation of concentration. The general formula used was:

$$X_k = \left(W_{k_o}X_{k_o} + \frac{k - k_o}{k_n - k_o}(W_{k_n}X_{k_n} - W_{k_o}X_{k_o})\right) W_k^{-1} \quad (1)$$

where: X = Streamflow, conductance, or solute concentration
W = A weighting factor
k = Julian date within a period of missing values
k_o = Last Julian date with observed data before the period of missing values
k_n = First Julian date with observed data after the period of missing values

Weighting factors in equation 1 are defined as follows:

1. Streamflow: $W_k = 1$, for all k

2. *Conductance:* $W_k = 1/Q_k^B$, where B is the slope of the log-log regression of daily conductance on daily streamflow (Q) for the entire period of unregulated flow. $W_k = 1$, if B is not significantly different from 0 (because of major flow regulation).

3. Solute concentrations: $W_k = 1/L_k$, where L is specific conductance on day k.

For streamflow interpolation equation 1 is linear with respect to time.

Conductance and concentration are transformed by the weighting factors into parameters (a_k and b_k in equations 2 and 3) that are expected to be relatively constant over short periods. For interpolation of conductance, equation 1 becomes a linear interpolation, with respect to time, of the parameter a_k in the equation:

$$L_k = a_k Q_k^B \quad (2)$$

Lane [9] found this power relationship to be generally applicable to natural streams in the Western United States. Conductance interpolation was not attempted when the missing value period included days of no flow.

The interpolation of solute concentration is a linear interpolation of the parameter b_k in the equation:

$$C_k = b_k L_k \quad (3)$$

Over small ranges, this linear relationship provides a good estimate of concentration. After interpolation, solute concentrations were adjusted to account for differences between the instantaneous specific conductance (L_S) at the time of sample collection and the mean daily conductance (L_D), if the latter value was available.

$$C_k = C_k \frac{L_D}{L_S} \quad (4)$$

This adjustment was made only for dates with continuously recorded specific conductance. It was made to correct potentially nonrepresentative instantaneous sample concentrations to average conditions on the sample date.

Interpolations were limited to intervals of 20 days for streamflow and conductance, and 60 days for solute concentrations. The effect of the length of the missing value period on the accuracy of specific conductance estimates was tested using data from the Colorado River at Cisco, Utah. Artificial gaps of varying length were created in the conductance record, and generated estimates were compared with measured values. Standard errors were 6.8 and 10.2 percent of the observed mean for 7-day and 20-day intervals, respectively. Although increasing the interpolation interval decreased the estimation accuracy, a 10 percent standard error was not considered unreasonable.

The effect of the length of the missing value period on the accuracy of solute concentration estimates was tested using data from the discrete sampling period for the Colorado River at Lees Ferry, Arizona. Increasing the maximum period from 45 to 60 days resulted in change of only 3 percent in the average monthly concentrations for the sum of 6 ions. In addition, the number of months with inadequate data for computing monthly means, as defined below, was reduced by 21 percent. To maintain representative data on the maximum number of months, the interpolation interval was set at 60 days, which allows interpolation between any two samples collected in consecutive calendar months. Testing the accuracy of streamflow interpolation was considered unnecessary because of the infrequent occurrence of gaps in these data.

Following interpolation, monthly mean values of streamflow and flow-weighted concentrations were computed from daily values. When measured or estimated values were unavailable for more than 25 percent of the days in a month, analysis of that month was discontinued. Therefore, the resultant monthly values are intended to preserve the maximum amount of information from existing data without masking long-term trends or including unreasonable estimates. Monthly values are listed in table 3 of appendixes B through P.

Analysis of Seasonality

Prior to statistical analysis, the generated monthly data were tested for seasonal variability. Normalized deviations (Δ) from the annual mean were computed for each month using the formula:

$$\Delta = \frac{X_{y,m} - \bar{X}_y}{\bar{X}_y} \quad (5)$$

where: X = streamflow, solute concentration, or load
$\bar{X}$ = the annual mean of each parameter
y = year
m = month

The average monthly values for Δ were then plotted to determine the seasonal pattern. Figure 3 shows the seasonal variation in streamflow for the Colorado River at Cisco, Utah. A peak runoff period in May and June is clearly indicated. April and July are transition months, and the remaining months appear to constitute a baseflow period. However, chemical variation, shown in figure 4, indicates a

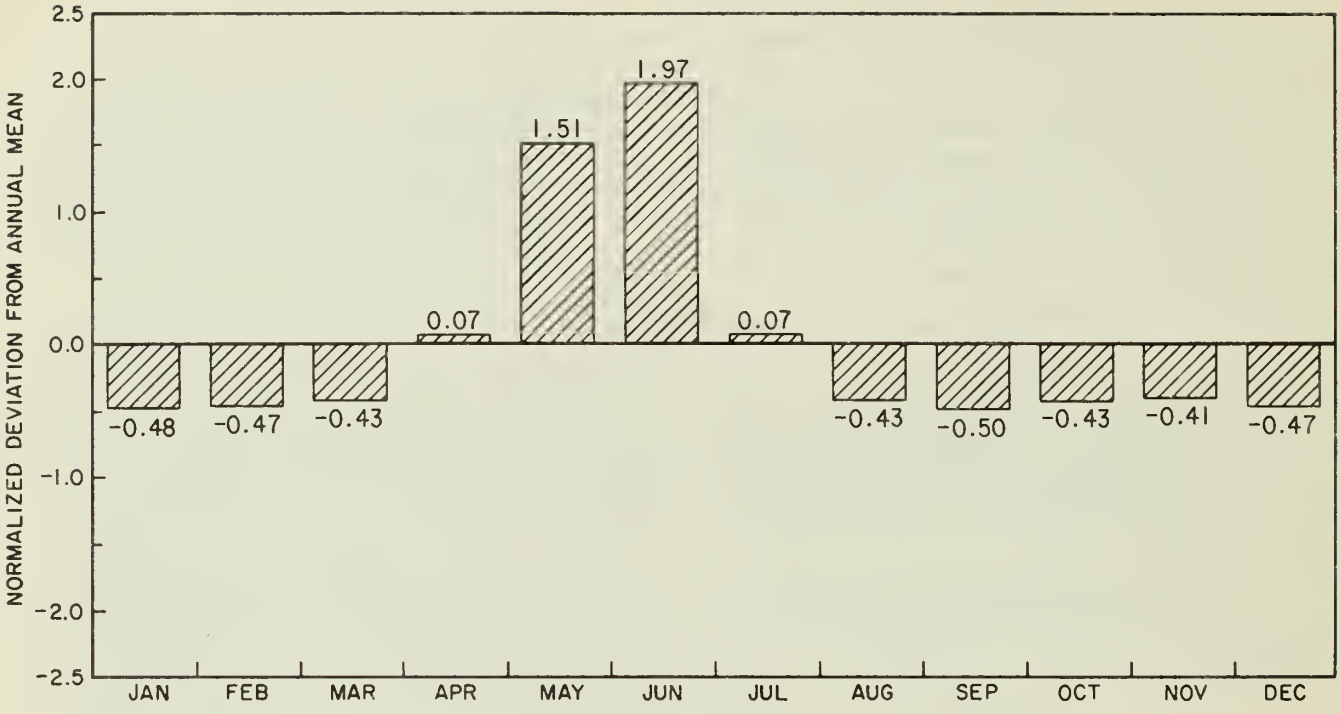

Figure 3. — Average monthly streamflow variation, Colorado River at Cisco, Utah, 1928–1982.

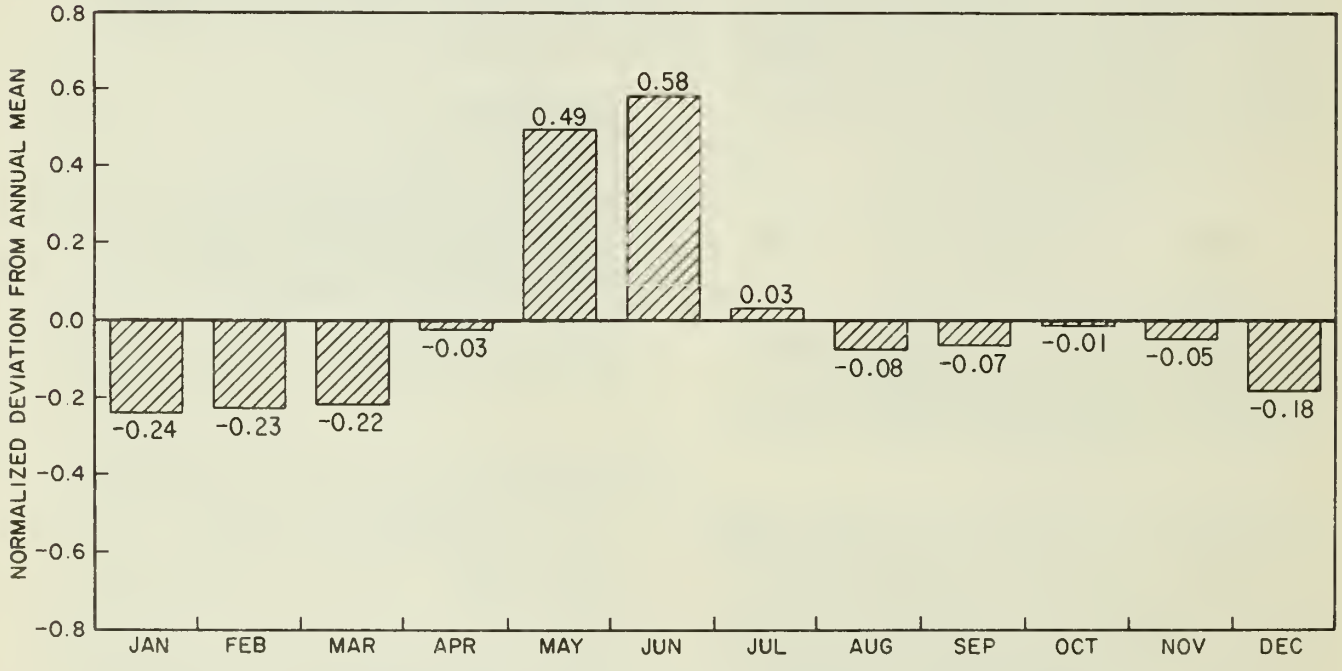

Figure 4. — Average monthly variation in TDS load, Colorado River at Cisco, Utah, 1928–1982.

difference between the August–November and December–March periods. Higher concentrations in the former are mainly caused by calcium and sulfate, which are predominant in irrigation return flow. Other gage sites gave similar results, unless streamflow was regulated by an upstream reservoir. Therefore, the annual cycle was divided into three seasons: (1) baseflow, December–March, (2) peak runoff, May–June, and (3) return flow, August–November.

CONCENTRATION-STREAMFLOW RELATIONSHIPS

In unregulated streams salinity generally varies inversely with streamflow. Possible causes of this inverse relationship and a review of several mathematical models proposed to describe this relationship are listed by Lane [9]. In evaluating the beneficial effects of salinity control projects, concentration–streamflow models are useful to correct the salinity for the effect of the natural variability of streamflow before and after construction of the project. In this report, these models are used in multiple regression analyses to remove predictable, short-term fluctuations in concentration, thus allowing more precise estimates of long-term changes in concentration and load. This chapter develops a theoretical model with two parameters that have physical meaning and compares the results of this model with those obtained from the power equation.

The power equation is an empirical model commonly used to describe the concentration–streamflow relationship [9]. This equation (with solute subscripts omitted) is:

$$C = b_1 Q^{b_2} \tag{6}$$

where: C = Concentration
Q = Streamflow
b_1, b_2 = Empirical parameters estimated by regression

The parameter b_2 ranges from zero, where concentration is independent of streamflow, to minus one, where load is independent of streamflow. Equation 6 yields unrealistically high estimates of concentrations at low flows, because C approaches infinity as Q approaches zero.

Because the power model fails at low flows and because the parameter b_1 and b_2 have no physical meaning, a theoretical residence time model is derived based on the assumptions listed below. Assumptions 2 and 4 may represent serious oversimplifications of the physical system.

1. The solute concentration in rain or snowmelt is negligible.

2. The contact area of dissolvable solids is independent of the streamflow.

3. The mass transfer coefficient for the dissolution of solids is constant.

4. The solubility of any solute is constant; i.e., the solubility is independent of the chemical composition of both the dissolving solids and the aqueous solution.

The differential equation (with solute subscripts omitted) for dissolution is:

$$QdC' = -k(C'-C_s)dA' \tag{7}$$

where: Q = Streamflow (m^3/s)
C' = Solute concentration after Q has contacted A', the area of solid surface (g/m^3)
C_s = Solute solubility (g/m^3)
k = Mass transfer coefficient (m/s)
A' = Solid-liquid contact area (m^2)

By assumption 1, the boundary condition is:

$$C(A' = 0) = 0 \tag{8}$$

By assumptions 3 and 4, the solution to equation 7 is:

$$C = C_s [1-\exp(-\tau)] \tag{9}$$

where τ, the dimensionless residence time, is defined by:

$$\tau = \frac{kA}{Q} \tag{10}$$

and A is the total solid-liquid contact area upstream of the gaging station. Equation 9 is of the form:

$$C = b_1 [1-\exp(-b_2/Q)] \tag{11}$$

where b_1 and b_2 are parameters to be estimated by regression, based on observed values of concentration and streamflow. The parameter b_1 represents the solute solubility, and b_2 represents the product of the mass transfer coefficient and the total solid-liquid contact area. The residence time equation yields realistic values of concentrations at zero streamflow (infinite residence time), where the solute concentration approaches solubility, and at infinite streamflow (zero residence time), where the concentration approaches zero (see fig. 5).

To test the effectiveness of the power and residence time equations in describing the relationship between monthly values of concentration and streamflow, regressions were conducted for 6 solutes and their sum. Regressions were run for each of the three seasons at 12 different gaging

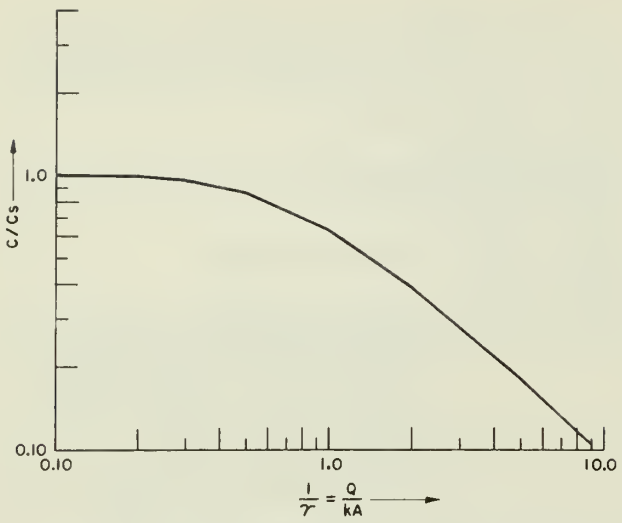

Figure 5. — Residence time equation on log-log scale. (The power equation would yield a straight line with the slope equal to the power term b_2 in equation 6.)

stations on the Colorado River (see tables 4 and 5 in appendixes B through O). Nonlinear regressions of equations 6 and 11 used the SPSS (Statistical Package for the Social Sciences) subprogram NONLINEAR [11, 12] with the Marquardt algorithm [13]. Values only from periods of minimum flow regulation upstream of the gaging stations are included in the regression analyses. By dividing the year into three seasons, assumptions 2 and 4 for the residence time model imply that b_1 and b_2 in equation 11 are constant only for one season. Although the solute solubility parameter (b_1 in equation 11) may be independent of the season, seasonal values were estimated to maintain the same degrees of freedom used in the power regression.

Because precision in the chemical analyses is generally proportional to the magnitude of the solute concentrations, a weighting factor of C_m^{-2} is used in the nonlinear regressions. With this weighting factor, the RMS (root-mean-square) error, or standard deviation of the residuals, is dimensionless and becomes the fractional standard deviation. For the weighted regression, the RMS error is defined as:

$$\text{RMS error} = \left(\frac{\sum_{j=1}^{n} \left(\frac{C_{j,obs} - C_{j,pred}}{C_{j,obs}} \right)^2}{n-k} \right)^{0.5} \qquad (12)$$

where: $C_{j,obs}$ = Observed monthly value of concentration

$C_{j,pred}$ = Monthly value of concentration estimated from streamflow by the power or residence time equation

n = Number of observations

k = Number of estimated parameters ($k = 2$ for equations 6 and 11)

n–k = degrees of freedom

An RMS error of 0.10 indicates (assuming random normally distributed residuals and greater than 30 degrees of freedom) an approximately 68-percent probability that the estimated and observed values of concentrations differ by less than 10 percent.

Although complete model evaluation requires examination of the residuals for any systematic bias in estimating concentration, residual examination is omitted from this report because of the large number of regressions. A preliminary comparison of the accuracy of the models can be made from the RMS errors summarized in table 2. The missing values in table 2 result from difficulties in computing that regression. Based on the RMS errors, the power equation is more accurate than the residence time equation for the peak flow months of May and June. For the other two seasons the RMS errors differ little. Neither equation is accurate for the Dolores River, near Cisco, Utah, where the RMS errors are generally greater than 0.20. Both equations are used in the multiple regression analyses in the next section to estimate long-term changes in concentration.

The regression results of the power equation (see table 4 in appendixes B through O) indicate that for several solutes at several locations, the streamflow has only a minor effect on the concentration. Based on the estimated values of the power term (b_2 in equation 6) that are greater than –0.20, the bicarbonate concentration is relatively independent of the streamflow for all stations (see table 3). By the same criteria, the calcium concentration varies little with the streamflow at 7 of the 12 stations.

LONG-TERM CHANGES FOR PERIODS OF MINOR FLOW REGULATION

The object of this section is to determine whether the monthly values of concentration, load, or mass fraction of any of the six major ions (calcium, magnesium, and sodium cations; and chloride,

Table 2. — *Root-mean-square errors (weighted by C_m^{-2}) of two equations describing the concentration-streamflow relationship*

RMS error of $C_m = b_1 Q_1^{b_2}$ / RMS error of $C_m = b_1[1 - \exp(-b_2/Q_m)]$

Period	Season	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate	Sum of six ions
Colorado River near Cameo, Colorado								
1933–45	Dec.–Mar.	0.057/0.052	0.068/0.062	0.064/0.058	0.066/0.064	0.066/0.062	0.054/0.049	0.053/0.049
	May–Jun.	0.127/0.130	0.241/	0.078/	0.085/0.087	0.070/0.070	0.098/0.098	0.052/0.053
	Aug.–Nov.	0.045/0.066	0.239/0.226	0.188/	0.063/0.068	0.067/0.070	0.039/0.045	0.042/0.058
Gunnison River near Grand Junction, Colorado								
1931–64	Dec.–Mar.	0.107/0.107	0.111/0.110	0.142/0.142	0.165/0.164	0.121/0.120	0.082/0.082	0.103/0.103
	May–Jun.	0.108/0.185	0.151/0.206	0.180/0.233	0.303/0.327	0.125/0.165	0.090/0.116	0.094/0.152
	Aug.–Nov.	0.121/0.125	0.172/0.156	0.176/0.179	0.187/0.205	0.145/0.141	0.097/0.084	0.128/0.129
Dolores River near Cisco, Utah								
1951–82	Dec.–Mar.	0.324/0.324	0.348/0.343	0.379/0 371	0.393/0.382	0.334/0.329	0.823/	0.337/0.332
	May–Jun.	0.198/0.253	0.225/0.306	0.061/	0.244/	0.200/0.280	0.281/0.289	0.181/0.268
	Aug.–Nov.	0.237/0.270	0.184/0.199	0.344/0.342	0.396/0.392	0.288/0.304	0.947/	0.221/0.236
Colorado River near Cisco, Utah								
1928–46	Dec.–Mar.	0.084/0.087	0.103/0.105	0.109/0.110	0.137/0.137	0.115/0.118	0.065/0.067	0.085/0.087
	May–Jun.	0.092/0.117	0.146/0.163	0.107/0.105	0.122/0.119	0.127/0.145	0.126/0.121	0.087/0.115
	Aug.–Nov.	0.097/0.117	0.090/0.105	0.114/0.117	0.245/0.254	0.114/0.127	0.080/0.066	0.077/0.096
Green Basin								
Green River near Green River, Wyoming								
1951–62	Dec.–Mar.	0.095/0.095	0.155/0.152	0.149/0.154	0.140/0.149	0.198/0.199	0.089/0.092	0.137/0.139
	May–Jun.	0.135/0.162	0.217/0.240	0.138/0.164	0.197/0.223	0.170/0.192	0.139/0.151	0.139/0.172
	Aug.–Nov.	0.182/0.182	0.158/0.157	0.150/0.150	0.179/0.179	0.194/0.192	0.106/0.106	0.139/0.138
Yampa River near Maybell, Colorado								
1950–82	Dec.–Mar.	/0.112	0.201/0.196	0.183/0.165	0.256/0.246	0.291/	0.102/0.101	0.140/0.124
	May–Jun.	0.241/	0.392/0.396	0.336/0.341	0.376/0.388	0.376/	0.265/	0.283/
	Aug.–Nov.	0.124/0.122	0.194/0.182	0.215/0.200	0.301/0.295	0.223/0.219	0.129/0.126	0.145/0.145
White River near Watson, Utah								
1950–79	Dec.–Mar.	0.108/0.108	0.114/	0.249/	0.400/	0.131/	0.091/	0.155/
	May–Jun.	0.122/0.131	0.148/0.171	0.252/0.261	0.340/0.328	0.173/0.196	0.128/0.139	0.129/0.150
	Aug.–Nov.	0.103/	0.131/0.134	0.229/	0.384/	0.140/	0.091/	0.117/
Green River at Green River, Utah								
1928–61	Dec.–Mar.	0.079/0.086	0.122/0.117	0.104/0.105	0.110/0.130	0.113/0.111	0.073/0.077	0.079/0.082
	May–Jun.	0.112/	0.205/	0.206/0.214	0.151/0.164	0.214/0.220	0.132/	0.144/0.145
	Aug.–Nov.	0.110/	0.184/0.180	0.166/0.168	0.174/0.183	0.180/0.180	0.193/0.092	0.118/0.120

Table 2. — *Root-mean-square errors (weighted by C_m^{-2}) of two equations describing the concentration-streamflow relationship* — Continued

Period	Season	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate	Sum of six ions
San Rafael River near Green River, Utah								
1947-65	Dec.-Mar.	0.105/	0.136/	0.150/	0.136/0.161	0.134/0.148	0.146/	0.115/
	May-Jun.	0.134/0.237	0.159/0.291	0.216/0.289	0.183/0.286	0.191/0.280	0.060/0.062	0.152/0.263
	Aug.-Nov.	0.175/0.202	0.320/0.308	0.423/0.436	0.251/0.291	0.208/0.218	0.204/0.200	0.194/0.203
San Juan Basin								
San Juan River near Bluff, Utah								
1929-40	Dec.-Mar.	0.073/0.101	0.108/0.128	0.153/0.165	0.137/0.156	0.116/0.138	0.070/0.075	0.088/0.110
	May-Jun.	0.100/0.120	0.139/0.141	0.208/0.247	0.324/0.143	0.150/0.182	0.098/0.103	0.107/0.138
	Aug.-Nov.	0.149/0.185	0.186/0.213	0.259/0.301	0.167/0.213	0.211/0.255	0.125/0.131	0.177/0.218
San Juan River near Bluff, Utah								
1929-61	Dec.-Mar.	0.078/0.104	0.129/0.139	0.155/0.175	0.172/0.183	0.110/0.132	0.073/0.076	0.090/0.114
	May-Jun.	0.136/0.157	0.219/0.232	0.210/0.236	0.192/0.212	0.175/0.202	0.142/	0.146/0.172
	Aug.-Nov.	0.143/0.166	0.232/0.235	0.222/0.264	0.188/0.223	0.189/0.228	0.131/0.130	0.157/0.196
Lower Colorado Basin								
Colorado River at Lees Ferry, Arizona								
1927-41	Dec.-Mar.	0.055/0.075	0.036/0.052	0.056/0.074	0.056/0.066	0.052/0.069	0.040/0.055	0.040/0.061
	May-Jun.	0.028/0.026	0.082/0.094	0.208/0.201	0.051/0.049	0.074/0.064	0.059/0.062	0.059/0.058
	Aug.-Nov.	0.191/	0.138/0.151	0.170/0.194	0.145/0.157	0.211/0.222	0.066/0.070	0.165/0.181
Colorado River at Lees Ferry, Arizona								
1927-61	Dec.-Mar.	0.071/0.079	0.124/0.123	0.063/0.068	0.059/0.061	0.079/0.084	0.071/0.073	0.051/0.058
	May-Jun.	0.129/0.143	0.164/0.179	0.159/0.173	0.144/0.156	0.128/0.147	0.133/0.140	0.105/0.127
	Aug.-Nov.	0.152/0.164	0.167/0.176	0.152/0.155	0.150/0.149	0.167/0.179	0.096/0.095	0.126/0.142
Colorado River near Grand Canyon, Arizona								
1925-41	Dec.-Mar.	0.063/0.071	0.086/0.086	0.070/0.078	0.064/0.064	0.075/0.080	0.059/0.064	0.057/0.064
	May-Jun.	0.111/0.128	0.127/0.140	0.133/0.149	0.104/0.108	0.147/0.166	0.107/0.112	0.106/0.127
	Aug.-Nov.	0.149/	0.122/0.155	0.129/0.164	0.088/0.107	0.169/0.200	0.072/0.090	0.126/0.163
Colorado River near Grand Canyon, Arizona								
1925-61	Dec.-Mar.	0.057/0.064	0.100/0.099	0.078/0.086	0.144/0.147	0.080/0.084	0.064/0.066	0.056/0.062
	May-Jun.	0.143/	0.153/0.166	0.139/0.111	0.098/0.104	0.144/0.164	0.167/0.168	0.125/0.140
	Aug.-Nov.	0.142/0.153	0.138/0.154	0.129/0.147	0.093/0.105	0.164/0.182	0.098/0.100	0.118/0.139

Table 3. — *Identification of stations, seasons, and solutes where solute concentration (C) or load (L) is relatively independent of streamflow*

Period	Season	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate	Sum of six ions
Upper Colorado Basin								
Colorado River near Cameo, Colorado								
1933–45	Dec.–Mar.							
	May–Jun.							
	Aug.–Nov.							
Gunnison River near Grand Junction, Colorado								
1931–64	Dec.–Mar.						C	
	May–Jun.						C	
	Aug.–Nov.						C	
Dolores River near Cisco, Utah								
1951–82	Dec.–Mar.	C	C			C		
	May–Jun.			L	L		C	
	Aug.–Nov.							
Colorado River near Cisco, Utah								
1928–46	Dec.–Mar.							
	May–Jun.				L		C	
	Aug.–Nov.						C	
Green Basin								
Green River near Green River, Wyoming								
1951–62	Dec.–Mar.	C	C				C	C
	May–Jun.	C					C	
	Aug.–Nov.						C	
Yampa River near Maybell, Colorado								
1950–82	Dec.–Mar.	C	C			C		C
	May–Jun.	C	C	C		C	C	C
	Aug.–Nov.	C						
White River near Watson, Utah								
1950–79	Dec.–Mar.	C	C	C	C		C	C
	May–Jun.						C	
	Aug.–Nov.	C					C	
Green River at Green River, Utah								
1928–61	Dec.–Mar.	C	C	C		C	C	C
	May–Jun.	C	C			C	C	C
	Aug.–Nov.	C	C			C	C	C

Table 3. — *Identification of stations, seasons, and solutes where solute concentration (C) or load (L) is relatively independent of streamflow* — Continued

Period	Season	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate	Sum of six ions
San Rafael River near Green River, Utah								
1947–65	Dec.–Mar.			C			C	
	May–Jun.						C	
	Aug.–Nov.	C	C	C		C	C	C
San Juan Basin								
San Juan River near Bluff, Utah								
1929–40	Dec.–Mar.	C		C			C	C
	May–Jun.	C	C				C	
	Aug.–Nov.	C	C				C	C
San Juan River near Bluff, Utah								
1929–61	Dec.–Mar.						C	
	May–Jun.	C					C	
	Aug.–Nov.	C					C	C
Lower Colorado Basin								
Colorado River at Lees Ferry, Arizona								
1927–41	Dec.–Mar.	C				C		
	May–Jun.						C	
	Aug.–Nov.	C				C	C	C
Colorado River at Lees Ferry, Arizona								
1927–61	Dec.–Mar.						C	
	May–Jun.						C	
	Aug.–Nov.	C					C	
Colorado River near Grand Canyon, Arizona								
1925–41	Dec.–Mar.						C	
	May–Jun.						C	
	Aug.–Nov.	C					C	
Colorado River near Grand Canyon, Arizona								
1925–61	Dec.–Mar.	C					C	
	May–Jun.						C	
	Aug.–Nov.	C					C	

In the power equation:

$$C_m = b_1 Q_m^{b_2}$$

the solute concentration is identified as being relatively independent of streamflow when the estimated value of b_2 is greater than –0.20 and the weighted RMS error is less than 0.50. For solute load, independence is identified for values of b_2 less than –0.80.

sulfate, and bicarbonate anions) had changed significantly before construction of the major upstream dams. Monthly values for the solute concentration are the flow-weighted means of daily concentrations estimated by the procedure described under DATA BASE DEVELOPMENT. The monthly solute load is computed by:

$$J_{i,m} = C_{i,m} Q_m / 1000 \qquad (13)$$

where: $J_{i,m}$ = Monthly value of load of solute i in kg/s
$C_{i,m}$ = Monthly value of concentration of solute i in mg/L
Q_m = Monthly value of streamflow in m^3/s computed as the mean of daily measurements (see DATA BASE DEVELOPMENT)
i = Solute (Ca^{+2}, Mg^{+2}, Na^{+2}, Cl^-, SO_4^{-2}, HCO_3, or the sum of these six ions)

The monthly solute mass fraction $W_{i,m}$ expressed as a percent of each of the six major ions is computed by:

$$W_{i,m} = \frac{C_{i,m}}{C_{7,m}} \times 100 \text{ percent} \qquad (14)$$

where: $C_{7,m}$ = sum of the concentrations of the six major ions (refer to DATA BASE DEVELOPMENT)

Because concentration and load are generally strong functions, and mass fraction may be a weak function of streamflow, multiple regression analyses are used to determine the existence of long-term trends in these parameters. In determining the existence of long-term changes in salinity during periods of minor flow regulation, the following equations (with solute subscripts omitted) can be used in the regression analyses:

$$J_m = b_1 + b_2 Q_m + b_3 t \qquad (15)$$

$$C_m = b_1 + b_2 Q_m + b_3 t \qquad (16)$$

$$W_m = b_1 + b_2 Q_m + b_3 t \qquad (17)$$

$$C_m = b_1 Q_m^{b_2} t^{b_3} \qquad (18)$$

$$W_m = b_1 Q_m^{b_2} t^{b_3} \qquad (19)$$

$$C_m = b_1 Q_m^{b_2} \exp(b_3 t) \qquad (20)$$

$$W_m = b_1 Q_m^{b_2} \exp(b_3 t) \qquad (21)$$

$$C_m = b_1[1 - \exp(-[b_2 + b_3 t]/Q_m)] \qquad (22)$$
(weighting factor = C_m^{-2})

where: b_1, b_2, b_3 = Parameters estimated by regression. Different values of these parameters are estimated for each equation.
t = Year in the twentieth century (e.g., for the year 1950, t = 50).

For evaluating the statistical significance of long-term changes in the water quality parameters, the regression paramenter b_3 in each of the above eight equations is tested against the null hypothesis that b_3 is zero.

Equations 15, 16, and 17 are standard, unweighted, empirical linear equations for use in multiple linear regression. The computed statistical significance of b_2 in equation 15 is ignored because of the intrinsic correlation between streamflow and solute load, which is computed as the product of monthly values of streamflow and concentration. The estimated long-term linear trend for the dependent variable y (J_m, C_m, or W_m) in equations 15, 16, and 17 is:

$$\left(\frac{\delta y}{\delta t}\right)_{Q_m} = b_3 \qquad (23)$$

where the subscript Q_m indicates that the derivative is evaluated at a constant value of Q_m.

Equations 18 and 19 are unweighted empirical power equations, whose logarithms are linear and solvable by multiple linear regression. Power equations are often used for parameters with log-normal distributions. The power equation for concentration (equation 18) is used because of the accuracy of the power equation (equation 6) for describing the concentration-streamflow relationship. The estimated rate of change of the dependent variable y (C_m or W_m) in equations 18 and 19 is:

$$\left(\frac{\delta y}{\delta t}\right)_{Q_m} = b_3 y / t \qquad (24)$$

and the average long-term trend can be estimated by evaluating equation 24 at the mean values of y and t. The average long-term trend for load associated with the trend in concentration can be estimated by:

$$\left(\frac{\delta J_m}{\delta t}\right)_{\bar{Q}_m} = b_3 \bar{Q}_m \bar{C}_m/(1000\,\bar{t}) \qquad (25)$$

where b_3 is estimated by regression with equation 18 and $\bar{Q}_m$, $\bar{C}_m$, and $\bar{t}$ are the mean values of Q_m, C_m, and t.

Equation 20 was also derived from the empirical power relationship by allowing b_1 in equation 5 to vary with time. With a linear change in b_1, equation 6 may be written as:

$$C_m = b_1 (1 + b_3 t)\, Q_m^{b_2} \qquad (26)$$

which can be approximated by equation 20 for absolute values of $b_3 t$ less than 1.0. Multiple linear regression can be used with the logarithms of equations 20 and 21 to estimate the parameters b_1, b_2, and b_3. The rate of change of the dependent variable y (C_m or W_m) in equation 20 and 21 is:

$$\left(\frac{\delta y}{\delta t}\right)_{Q_m} = b_3 y \qquad (27)$$

and the average long-term trend can be estimated by evaluating equation 27 at the mean value of y. The average long-term trend for load associated with the trend in concentration can be estimated by:

$$\left(\frac{\delta J_m}{\delta t}\right)_{\bar{Q}_m} = b_3 \bar{Q}_m \bar{C}_m/1000 \qquad (28)$$

where b_3 is the regression parameter in equation 20.

Equation 22 is the residence time equation with an additional regression parameter, b_3, for long-term changes in residence time caused by changes in the solid-liquid mass transfer coefficient or in the contact area. Equation 22 is not linear with respect to the parameters b_1, b_2, and b_3 and must be solved by weighted, nonlinear regression. The rate of change of C_m is:

$$\left(\frac{\delta C_m}{\delta t}\right)_{Q_m} = b_3 (b_1 - C_m)/Q_m \qquad (29)$$

and the average long-term trend can be estimated by evaluating equation 29 at the mean values of C_m and Q_m. The average long-term trend for the load is:

$$\left(\frac{\delta J_m}{\delta t}\right)_{\bar{Q}_m} = b_3 (b_1 - \bar{C}_m)/1000 \qquad (30)$$

Equations 29 and 30 are valid approximations for the average long-term trends only when the estimated value of b_1 is greater than $\bar{C}_m$. In equations 25, 28, and 30, the estimated long-term trends for the load associated with trends in concentration are intended to be independent of the long-term changes in streamflow. Changes in the load associated with changes in streamflow are estimated by:

$$\left(\frac{\delta J_m}{\delta t}\right)_{C_m} = \frac{\bar{C}_m}{1000}\,\frac{\delta^{Q_m}}{\delta t} \qquad (31)$$

In regression equation 15 for load the parameter b_3 measures both effects, and thus includes the additional changes in load due to transmountain diversions or other diversions with no return flow. The long-term trend for the load associated with a linear change in only concentration can be estimated from the regression results of equation 16 by:

$$\left(\frac{\delta J_m}{\delta t}\right)_{\bar{Q}_m} = b_3 \bar{Q}_m/1000 \qquad (32)$$

Multiple linear regressions of equations 15 through 21 used FORTRAN subroutines BECOVM and RLMUL of the IMSL (International Mathematical and Statistical Libraries, Inc.) Library [14]. Nonlinear regression of equation 22 employed the SPSS subprogram NONLINEAR with the Marquardt algorithm. Complete results of the regression analyses of equations 15 through 20 are contained in tables 6 through 9 of appendixes B through O.

Tables 4 through 7 summarize the long-term trends for the concentration and associated long-term trends for the load estimated by regression of concentration equations 16, 18, 20, and 22 where the parameter b_3 is significantly different from zero at the 95-percent confidence level. Table 8 lists the statistically significant trends with the highest confidence levels from tables 4 through 7. The four equations yielded similar results with several cases where the estimated long-term

trends are identical to two decimal places. Separate estimates of b_1 for each season would result in a better fit to the data and in more precise estimates of long-term trends by equations 30 and 31, where the difference between b_1 and $\bar{C}_m$ is evaluated. In several cases in table 7, $\bar{C}_m$ is larger than b_1 (see equations 30 and 31), causing a reversal in the sign of the estimated long-term trends. In these cases, only the sign of b_3 in equation 22 is listed.

Tables 9, 10, and 11 contain the estimated long-term trends for mass fraction where significant values of b_3 are indicated in equations 17, 19, and 21. The three empirical equations estimated almost identical long-term trends in mass fractions. Table 12 contains all trends that are indicated to be significant by any of the three mass fraction regressions.

Where no trend is indicated for an entry in tables 4 through 12, an actual trend may exist, but the data do not justify rejection of the null hypothesis of zero long-term trend. Only a few (4 to 15) months of data are available for the Cameo station, which was included in the trend analysis because of its importance as a major gaging station on the Colorado River. Generally, for each row in tables 4 through 8, the sum of the significant trends in concentration for the six individual ions (columns 3 through 8) is approximately equal to the significant trend estimated for the sum of the six ions (column 9). For each row of mass fractions in tables 9 through 12, the sum of the significant trends of the individual ions is approximately zero.

Long term declines in the TDS (sum of six ions), corrected for the variation in streamflow by multiple regression, are evident at 8 of the 12 gaging stations (see table 8). The Dolores River near Cisco and the Yampa River near Maybell are the only stations indicated to be experiencing an increase in salinity.

At eight gaging stations the regression results indicate a negative trend in sulfate ion concentration and mass fraction (see tables 8 and 12). Declines in the concentrations of magnesium and sodium ions are evident at seven stations (not including Cameo). For the base flow season of December to March, in the Colorado River at Lees Ferry and near the Grand Canyon, the concentrations of the sulfate, magnesium, and sodium ions have declined in stoichiometric proportions, causing a decline in TDS of approximately 2mg/L per year. Figures 6 through 9 and 10 through 13 illustrate the declines in magnesium and sulfate concentrations during December, January, February, and March in the Colorado River near the Grand Canyon. The y-variable is transformed to accommodate a two-dimensional figure. The y-variable in figures 6 through 8 and 10 through 12 is the ion concentration with a linear or power correction for the natural variability of streamflow. The regression lines are the results of the empirical multiple linear regressions (equations 15, 17, and 19). The y-variable in figures 9 and 13 is the estimated value of the product of the solid-liquid mass transfer coefficient (k) and the total solid-liquid contact area (A) upstream of the gaging station (see equations 8 and 9). The regression lines are the result of nonlinear regression with the residence time equation (equation 22).

IMPACT OF FLOW REGULATION

When an impoundment is created, upstream waters are mixed in the reservoir and quality fluctuations diminish. Water released downstream during periods of natural low flow decreases the normally high salt concentrations. In addition, chemical changes caused by the dissolution and precipitation of mineral salts within the reservoir may change the character of the release water [8]. At locations such as Lees Ferry, where flow is almost completely regulated, concentration is no longer related to flow. At other sites, where flow has become partially regulated, the concentration-flow relationship may be weakened or changed altogether. The impact of regulation must then be evaluated independent of streamflow. Therefore, two statistical analyses were used to test for changes in water quality as a function of time alone.

In both analyses, the monthly data were divided into two periods: (1) before 1963, and (2) after 1965. These represent the times before and after the filling of the Colorado River Storage Project reservoirs. Solute loads, mass fractions, and flow-weighted concentrations were computed for the three seasons: December–March, May–June, and August–November. Student's t test was then used to determine significant differences between mean seasonal values. Trends following regulation were tested by linear regression, with time as the sole independent variable. All stations were treated alike, even if the flow there did not become regulated during the 1963-65 period. The results could then be compared between stations and regulation impact could be separated from other basinwide influences. Complete results of these tests are displayed in tables 10 and 11 of appendixes B through P.

Table 4. — *Significant long-term trends in concentration (mg/(L·a)) by linear regression. Associated trends (kg/(s·a)) for solute loads are in parentheses*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				UPPER COLORADO BASIN				
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.								
1933-45	DEC-MAR	-	-	-	-	-	-	-
	MAY-JUNE	-	-	-4.01(-1.342)	-	-	-	-
	AUG-NOV	-	-	-	-	-	-	-
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT								
1931-64	DEC-MAR	-	- 46(-.012)	-1.26(-.033)	-.25(-.007)	-4.13(-.108)	-	-6.64(-.173)
	MAY-JUNE	-	-	-.82(-.163)	-	-	-	-
	AUG-NOV	-.96(-.028)	-.83(-.024)	-2.57(-.076)	-.44(-.013)	-7.83(-.240)	-	-12.15(-.361)
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT								
1951-82	DEC-MAR	-	-	-	-	-	4.49(.028)	-
	MAY-JUNE	-	.64(.041)	7.67(458)	10.97(.655)	4.55(.272)	-	24.54(1.465)
	AUG-NOV	-	-	8.49(.046)	14.93(.081)	-5.58(-.030)	3.89(.021)	21.01(.113)
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH								
1928-46	DEC-MAR	-.65(-.048)	-.43(-.032)	-	1.99(.147)	-6.62(-.489)	-.76(-.056)	-7.19(-.532)
	MAY-JUNE	-	-.23(-.147)	-.73(-.459)	-.56(-.349)	-2.90(-1.816)	-	-
	AUG-NOV	-	-.50(-.051)	-2.29(-.232)	-	-5.80(-.584)	-	-9.65(-.971)
				GREEN BASIN				
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.								
1951-62	DEC-MAR	-1.20(-.019)	-.78(-.013)	-	-	-4.67(-.078)	-2.23(-.037)	-10.46(-.174)
	MAY-JUNE	-	-.58(-.069)	-	-	-	-	-
	AUG-NOV	-1.90(-.045)	-.69(-.017)	-.81(-.019)	-	-5.24(-.123)	-2.41(-.057)	-11.18(-.263)
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.								
1950-82	DEC-MAR	-	.29(.003)	.28(.003)	-.28(-.003)	2.26(.022)	-	2.48(.024)
	MAY-JUNE	-	.11(.018)	-	-	.73(.115)	-	-
	AUG-NOV	-	.10(.001)	-	-.48(-.004)	.84(.007)	-	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT								
1950-79	DEC-MAR	-.36(-.004)	-	-1.30(-.015)	-1.74(-.020)	-1.38(-.016)	-	-4.83(-.056)
	MAY-JUNE	-.25(-.011)	-	-	-.42(-.018)	-	-	-
	AUG-NOV	-.43(-.005)	-	-1.14(-.013)	-1.81(-.020)	-1.06(-.012)	-	-4.25(-.048)
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA								
1928-61	DEC-MAR	-	-	-	-.43(-.029)	-	.36(.024)	-
	MAY-JUNE	-	-	-	-.08(-.037)	-	-	-
	AUG-NOV	-	-	-	-.41(-.029)	-	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV								
1947-65	DEC-MAR	-1.84(-.003)	-1.36(-.002)	-	-	-	-2.49(-.004)	-
	MAY-JUNE	-	-	-	-	-	-	-
	AUG-NOV	-	-	-10.52(-.022)	-	-29.93(-.063)	-	-38.07(-.080)

Table 4. — *Significant long-term trends in concentration (mg/(L·a)) by linear regression. Associated trends (kg/(s·a)) for solute loads are in parentheses* — Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				SAN JUAN BASIN				
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH								
1929-61	DEC-MAR	-	.09(.003)	.29(.009)	.34(.010)	-	-	-
	MAY-JUNE	-	-.07(-.012)	-	.05(.010)	-	-.51(-.093)	-
	AUG-NOV	-.35(-.014)	-	-	.29(.012)	-	-	-
				LOWER COLORADO BASIN				
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.								
1927-61	DEC-MAR	.22(.042)	-.36(-.068)	-.47(- 089)	-	-1.87(- 359)	-	-2.10(-.397)
	MAY-JUNE	.53(.689)	-	-	-	-	1.16(1.520)	-
	AUG-NOV	.91(.218)	-.22(-.052)	-	-	-	1.18(.282)	-
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,								
1925-61	DEC-MAR	-	-.14(-.029)	-.38(-.077)	-	-1.21(-.250)	.30(.062)	-1 50(-.308)
	MAY-JUNE	47(.629)	-	-	-	-	1.57(2.079)	1.81(2.407)
	AUG-NOV	-	-	-.65(-.169)	-	-	.88(.229)	-

Table 5. — *Significant long-term trends in concentration (mg/(L·a)) by log regression. Associated trends (kg/(s·a)) for solute loads are in parentheses*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				UPPER COLORADO BASIN				
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO								
1933-45	DEC-MAR	-	-	-	-	-	-	-
	MAY-JUNE	-	-	-2.93(-.980)	-	-	-	-
	AUG-NOV	-	-	-	-	-	-	-
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT								
1931-64	DEC-MAR	-	-.41(-.010)	-1.13(-.029)	-.23(-.006)	-3.81(-.100)	-	-6.04(-.158)
	MAY-JUNE	-	-.11(-.022)	-.33(-.066)	-	-	-	-
	AUG-NOV	-	-.58(-.017)	-1.66(-.049)	-.28(-.009)	-4.07(-.125)	-	-7.33(-.218)
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT								
1951-82	DEC-MAR	-	-	-	-	-	4.98(.032)	-
	MAY-JUNE	-	.21(.014)	1.64(.098)	1.56(.093)	1.23(.074)	-	5.88(.351)
	AUG-NOV	-	-	6.47(.035)	11.55(.063)	-5.66(-.031)	5.02(.027)	14.58(.079)
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH								
1928-46	DEC-MAR	-.61(-.045)	-.44(-.032)	-	1.90(.141)	-6.78(-.502)	-.76(-.056)	-7.01(-.519)
	MAY-JUNE	-	-	-	-	-1.79(-1.118)	-	-
	AUG-NOV	-	-.34(-.034)	-1.60(-.162)	-	-4.26(-.429)	.90(.091)	-5.73(-.576)
				GREEN BASIN				
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.								
1951-62	DEC-MAR	-1.32(-.021)	-.87(-.014)	-	-	-6.01(-.100)	-2.54(-.042)	-12.42(-.207)
	MAY-JUNE	-	-.67(-.079)	-	-	-1.67(-.202)	-	-
	AUG-NOV	-1.90(-.045)	-.68(-.016)	-.82(-.019)	-	-5.19(-.122)	-2.29(-.054)	-10.81(-.254)
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.								
1950-82	DEC-MAR	-	.26(.002)	.30(.003)	-.28(-.003)	1.96(.019)	-	2.35(.023)
	MAY-JUNE	-	-	.24(.038)	.07(.011)	.68(.107)	-	-
	AUG-NOV	-	.11(.001)	-	-.42(-.004)	.97(.008)	-	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT								
1950-79	DEC-MAR	-.36(-.004)	-	-1.41(-.016)	-1.99(-.023)	-1.47(-.017)	-	-4.99(-.058)
	MAY-JUNE	-.40(-.017)	-	-	-.59(-.025)	-	-	-
	AUG-NOV	-.42(-.005)	-	-1.17(-.013)	-1.95(-.022)	-1.02(-.012)	-	-4.20(-.047)
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA								
1928-61	DEC-MAR	-	-	-	-.35(-.024)	-	48(.033)	-
	MAY-JUNE	-	-	-	-	-	-	-
	AUG-NOV	-	-	-	-.30(-.022)	-	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV								
1947-65	DEC-MAR	-2.05(-.004)	-1.40(-.003)	-2.83(-.005)	-.43(-.001)	-12.53(-.022)	-2.93(-.005)	-17.51(-.031)
	MAY-JUNE	-	-1.31(-.017)	-3.29(-.041)	-.41(-.005)	-14.31(-.180)	-	-17.47(-.220)
	AUG-NOV	-	-3.30(-.007)	-12.78(-.026)	-1.07(-.002)	-33.85(-.070)	-	-43.49(-.090)

Table 5. — *Significant long-term trends in concentration (mg/(L·a)) by log regression. Associated trends (kg/(s·a)) for solute loads are in parentheses* — Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				SAN JUAN BASIN				
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH								
1929-61	DEC-MAR	-	.09(.003)	-	.31(.009)	-	-	-
	MAY-JUNE	-	-.07(-.012)	-	.06(.010)	-	- 47(-.086)	-
	AUG-NOV	-.36(-.015)	-	-	.22(.009)	-1.38(- 056)	-	-
				LOWER COLORADO BASIN				
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.								
1927-61	DEC-MAR	-	-.29(-.056)	-.38(-.072)	-	-1.59(-.305)	-	-1.80(-.341)
	MAY-JUNE	.41(.539)	-	-	-	-	.92(1.209)	-
	AUG-NOV	.67(.161)	-.22(-.054)	-.52(-.124)	-	-	1.09(.260)	-
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,								
1925-61	DEC-MAR	.11(.022)	-.11(-.022)	-.29(-.060)	-	-1.01(-.209)	.38(.079)	-
	MAY-JUNE	.50(.659)	-	-	-	-	1.64(2.178)	2.07(2.748)
	AUG-NOV	-	-	-.54(-.141)	-	-	.96(.250)	-

Table 6. — *Significant long-term trends in concentration (mg/(L·a)) by semilog regression. Associated trends (kg/(s·a)) for solute loads are in parentheses*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				UPPER COLORADO BASIN				
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.								
1933-45	DEC-MAR	-	-	-	-	-	-	-
	MAY-JUNE	-	-	-2.93(-.980)	-	-	-	-
	AUG-NOV	-	-	-	-	-	-	-
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT								
1931-64	DEC-MAR	-	-.45(-.012)	-1.26(-.033)	-.24(-.006)	-4.07(-.107)	-	-6.50(-.169)
	MAY-JUNE	-	-.12(-.025)	-.39(-.078)	-	-	-	-
	AUG-NOV	-	-.67(-.019)	-1.86(-.055)	-.30(-.009)	-4.53(-.139)	-	-8.10(-.241)
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT								
1951-82	DEC-MAR	-	-	-	-	-	5.25(.033)	-
	MAY-JUNE	-	.22(.014)	1.72(.103)	1.64(.098)	1.25(.074)	-	6.09(.364)
	AUG-NOV	-	-	6.71(.036)	12.07(.066)	-5.82(-.032)	5.31(.029)	15.39(.084)
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH								
1928-46	DEC-MAR	-.59(-.044)	-.42(-.031)	-	1.87(.138)	-6.63(-.490)	-.72(-.053)	-6.85(-.506)
	MAY-JUNE	-	-	-	-	-1.72(-1.074)	-	-
	AUG-NOV	-	-.32(-.032)	-1.50(-.152)	-	-3.97(-.400)	.88(.088)	-5.33(-.536)
				GREEN BASIN				
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.								
1951-62	DEC-MAR	-1.35(-.022)	-.88(-.014)	-	-	-6.12(-.102)	-2.52(-.042)	-12.56(-.209)
	MAY-JUNE	-	-.69(-.081)	-	-	-1.70(-.205)	-	-
	AUG-NOV	-1.91(-.046)	-.68(-.016)	-.82(-.019)	-	-5.21(-.123)	-2.26(-.053)	-10.81(-.254)
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.								
1950-82	DEC-MAR	-	.26(.002)	.29(.003)	-.29(-.003)	1.98(.019)	-	2.33(.023)
	MAY-JUNE	-	-	.24(.037)	-	.68(.107)	-	-
	AUG-NOV	-	.10(.001)	-	-.44(-.004)	.94(.008)	-	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT								
1950-79	DEC-MAR	-.38(-.004)	-	-1.50(-.017)	-2.10(-.025)	-1.52(-.018)	-	-5.28(-.062)
	MAY-JUNE	-.40(-.017)	-	-	-.62(-.027)	-	-	-
	AUG-NOV	-.42(-.005)	-	-1.24(-.014)	-2.03(-.023)	-1.03(-.012)	-	-4.32(-.049)
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA								
1928-61	DEC-MAR	-	-	-	-.38(-.026)	-	.47(.032)	-
	MAY-JUNE	-	-	-	-	-	-	-
	AUG-NOV	-	-	-	-.33(-.024)	-	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV								
1947-65	DEC-MAR	-2.01(-.004)	-1.45(-.003)	-2.90(-.005)	-.45(-.001)	-12.85(-.022)	-2.95(-.005)	-17.76(-.031)
	MAY-JUNE	-	-1.30(-.017)	-3.31(-.042)	-.42(-.005)	-14.30(-.180)	-	-17.53(-.221)
	AUG-NOV	-	-3.20(-.007)	-12.87(-.027)	-1.07(-.002)	-33.96(-.070)	-	-43.30(-.089)

Table 6. — *Significant long-term trends in concentration (mg/(L·a)) by semilog regression. Associated trends (kg/(s·a)) for solute loads are in parentheses* — Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				SAN JUAN BASIN				
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH								
1929-61	DEC-MAR	-	.08(.002)	-	.33(.010)	-	-	-
	MAY-JUNE	-	-.08(-.014)	-	.06(.011)	-		
	AUG-NOV	-.38(-.016)	-	-	.23(.009)	-1.43(-.058)	-.57(-.103)	-1.28(-.233)
							-	-
				LOWER COLORADO BASIN				
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.								
1927-61	DEC-MAR	.21(.039)	-.38(-.072)	-.47(-.090)	-	-1.98(-.375)	-	-2.18(-.414)
	MAY-JUNE	.52(.680)	-	-	-	-	1.15(1.511)	-
	AUG-NOV	.87(.208)	-.29(-.070)	-.61(-.146)	-	-	1.27(.304)	-
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,								
1925-61	DEC-MAR	-	-.13(-.026)	-.32(-.065)	-	-1.13(-.233)	.33(.067)	-1.17(-.241)
	MAY-JUNE	.49(.656)	-	-	-	-	1.60(2.124)	2.00(2.650)
	AUG-NOV	-	-.10(-.026)	-.58(-.151)	-	-1.51(-.403)	.91(.239)	-

Table 7. — *Significant long-term trends in concentration (mg/(L·a)) by nonlinear regression of the residence time equation. Associated trends (kg/(s·a)) for solute loads are in parentheses*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				UPPER COLORADO BASIN				
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.								
1933-45	DEC-MAR	-	-	-	-	-	-	-
	MAY-JUNE	-	-	-	-	-	-	-
	AUG-NOV	-	-	-	-	-	-	-
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT								
1931-64	DEC-MAR	-	-.36(-.009)	-1.27(-.033)	-.21(-.005)	-3.48(-.091)	-	-5.37(-.140)
	MAY-JUNE	-	-	-.40(-.079)	-	-.75(-.161)	05(.010)	-
	AUG-NOV	-	-.64(-.019)	-1.80(-.053)	-.24(-.007)	-4.56(-.140)	-	-7.24(-.215)
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT								
1951-82	DEC-MAR	-	-.03(-.000)	-4.04(-.025)	-6.26(-.039)	-1.52(-.010)	-	-11.73(-.074)
	MAY-JUNE	-	.05(.003)	-	-	.68(.041)	-	2.38(.142)
	AUG-NOV	-	-	2.38(.013)	-	-	-	6.43(.035)
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH								
1928-46	DEC-MAR	-	-	-	-	-5.07(-.374)	-	-
	MAY-JUNE	-	-	-	-	-1.36(-.854)	-	-
	AUG-NOV	-	-.33(-.034)	-1.41(-.143)	-2.00(-.202)	-4.14(-.417)	-	-
				GREEN BASIN				
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.								
1951-62	DEC-MAR	-1.58(-.026)	-.87(-.014)	-	-	-4.46(-.075)	-	-7.25(-.121)
	MAY-JUNE	-	-.73(-.087)	-	-	-1.65(-.198)	-	-
	AUG-NOV	-2.07(-.049)	-.65(-.016)	-.83(-.020)	-	-5.08(-.119)	-	-8.51(-.200)
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.								
1950-82	DEC-MAR	-	POSITIVE	.16(.002)	-.22(-.002)	POSITIVE	-	.47(.005)
	MAY-JUNE	-	-	-	-	-	-	-
	AUG-NOV	-	-	-	-.33(-.003)	.61(.005)	-	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT								
1950-79	DEC-MAR	-.50(-.006)	-	-1.18(-.014)	-1.78(-.021)	-	-	-
	MAY-JUNE	-	-	-	-.45(-.019)	.47(.020)	-	-
	AUG-NOV	-.36(-.004)	-	-	-	-	-	-
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA								
1928-61	DEC-MAR	-.09(-.006)	-.11(-.008)	-	-.35(-.024)	-	-	-.65(-.044)
	MAY-JUNE	-	-	-	-	-	-	-
	AUG-NOV	-	-	-	-.25(-.018)	-	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV								
1947-65	DEC-MAR	-	-1.25(-.002)	-1.07(-.002)	-.52(-.001)	-8.64(-.015)	-1.85(-.003)	-16.07(-.027)
	MAY-JUNE	-	-	-	-	-	-	-
	AUG-NOV	-	-	-	NEGATIVE	-	-	-

Table 7. — *Significant long-term trends in concentration (mg/(L·a)) by nonlinear regression of the residence time equation. Associated trends (kg/(s·a)) for solute loads are in parentheses* — Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				SAN JUAN BASIN				
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH								
1929-61	DEC-MAR	-.13(-.004)	-	-	.15(.004)	-	-	-
	MAY-JUNE	-	-.06(-.012)	-	.03(.006)	-.35(-.063)	NEGATIVE	-
	AUG-NOV	NEGATIVE	-.07(-.003)	-	.08(.003)	-.55(-.023)	-	NEGATIVE
				LOWER COLORADO BASIN				
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.								
1927-61	DEC-MAR	-	-.57(-.108)	-.47(-.088)	-	-2.19(-.419)	-	-2.10(-.398)
	MAY-JUNE	.21(.271)	-.08(-.106)	-	-	-	-	-
	AUG-NOV	-	-.23(-.056)	-.50(-.119)	-	-	POSITIVE	-
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,								
1925-61	DEC-MAR	.13(.026)	-.15(-.031)	-.31(-.064)	-	-1.12(-.231)	.56(.115)	-1.27(-.261)
	MAY-JUNE	.41(.544)	-	-	-	-	.80(1.058)	2.00(2.661)
	AUG-NOV	-	-.09(-.024)	-.32(-.084)	-	-	POSITIVE	-

Table 8. — *Significant long-term trends in concentration (mg/(L·a)) with highest confidence levels of the different regressions. Associated trends (kg/(s·a)) for solute loads are in parentheses*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				UPPER COLORADO BASIN				
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.								
1933-45	DEC-MAR	-	-	-	-	-	-	-
	MAY-JUNE	-	-	-2.93(-.980)	-	-	-	-
	AUG-NOV	-	-	-	-	-	-	-
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT								
1931-64	DEC-MAR	-	-.46(-.012)	-1.26(-.033)	-.25(-.007)	-4.13(-.108)	-	-6.64(-.173)
	MAY-JUNE	-	-.12(-.025)	-.39(-.078)	-	-.75(-.161)	.05(.010)	-
	AUG-NOV	-.96(-.028)	-.83(-.024)	-2.57(-.076)	-.28(-.009)	-7.83(-.240)	-	-12.15(-.361)
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT								
1951-82	DEC-MAR	-	-.03(-.000)	-4.04(-.025)	-6.26(-.039)	-1.52(-.010)	4.49(.028)	-11.73(-.074)
	MAY-JUNE	-	.22(.014)	1.72(.103)	1.64(.098)	1.23(.074)	-	6.09(.364)
	AUG-NOV	-	-	8.49(.046)	14.93(.081)	-5.82(-.032)	3.89(.021)	15.39(.084)
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH								
1928-46	DEC-MAR	-.65(-.046)	-.44(-.032)	-	1.87(.138)	-6.63(-.490)	-.76(-.056)	-7.19(-.532)
	MAY-JUNE	-	-.23(-.147)	-.73(-.459)	-.56(-.349)	-1.72(-1.074)	-	-
	AUG-NOV	-	-.34(-.034)	-1.41(-.143)	-2.00(-.202)	-4.14(-.417)	.88(.088)	-5.73(-.576)
				GREEN BASIN				
STATION 9217000 - GREEN R NR GREEN RIVER, WYO.								
1951-62	DEC-MAR	-1.58(-.026)	-.87(-.014)	-	-	-6.12(-.102)	-2.52(-.042)	-12.56(-.209)
	MAY-JUNE	-	-.73(-.087)	-	-	-1.65(-.198)	-	-
	AUG-NOV	-1.90(-.045)	-.68(-.016)	-.83(-.020)	-	-5.21(-.123)	-2.41(-.057)	-10.81(-.254)
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.								
1950-82	DEC-MAR	-	29(.003)	.28(.003)	-.29(-.003)	2.26(.022)	-	2.48(.024)
	MAY-JUNE	-	.11(.018)	.24(.038)	.07(.011)	.68(.107)	-	-
	AUG-NOV	-	.11(.001)	-	-.44(-.004)	.97(.008)	-	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT								
1950-79	DEC-MAR	-.38(-.004)	-	-1.50(-.017)	-2.10(-.025)	-1.52(-.018)	-	-4.83(-.056)
	MAY-JUNE	-.40(-.017)	-	-	-.62(-.027)	.47(.020)	-	-
	AUG-NOV	-.42(-.005)	-	-1.24(-.014)	-2.03(-.023)	-1.02(-.012)	-	-4.32(-.049)
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA								
1928-61	DEC-MAR	-.09(-.006)	-.11(-.008)	-	-.38(-.026)	-	.48(.033)	-.65(-.044)
	MAY-JUNE	-	-	-	-.08(-.037)	-	-	-
	AUG-NOV	-	-	-	-.41(-.029)	-	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV								
1947-65	DEC-MAR	-2.05(-.004)	-1.25(-.002)	-2.90(-.005)	-.52(-.001)	-12.85(-.022)	-1.85(-.003)	-16.07(-.027)
	MAY-JUNE	-	-1.31(-.017)	-3.31(-.042)	-.42(-.005)	-14.31(-.180)	-	-17.47(-.220)
	AUG-NOV	-	-3.30(-.007)	-12.78(-.026)	-1.07(-.002)	-33.85(-.070)	-	-43.49(-.090)

Table 8. — *Significant long-term trends in concentration (mg/(L·a)) with highest confidence levels of the different regressions. Associated trends (kg/(s·a)) for solute loads are in parentheses* — Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE	SUM OF SIX IONS
				SAN JUAN BASIN				
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH								
1929-61	DEC-MAR	-.13(-.004)	.09(.003)	.29(.009)	.33(.010)	-	-	-
	MAY-JUNE	-	-.06(-.012)	-	.06(.011)	-.35(-.063)	1.24(.227)	-1.28(-.233)
	AUG-NOV	.40(.016)	-.07(-.003)	-	.23(.009)	-.55(-.023)	-	.29(.012)
				LOWER COLORADO BASIN				
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.								
1927-61	DEC-MAR	.21(.039)	-.38(-.072)	-.47(-.090)	-	-1.96(-.375)	-	-2.18(-.414)
	MAY-JUNE	.52(.680)	-.08(-.106)	-	-	-	1.16(1.520)	-
	AUG-NOV	.91(.218)	-.23(-.056)	- 50(-.119)	-	-	1.09(.260)	-
STATION 9402500 - COLORADO R. NEAR GRAND CANYON.								
1925-61	DEC-MAR	.13(.026)	-.15(-.031)	-.38(-.077)	-	-1.12(-.231)	.56(.115)	-1.50(-.308)
	MAY-JUNE	.50(.659)	-	-	-	-	1.64(2.178)	2.07(2.748)
	AUG-NOV	-	-.09(-.024)	-.58(-.151)	-	-1.51(-.403)	.96(.250)	-

Table 9. — *Significant long-term trends in mass fraction (%/a) by linear regression*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				UPPER COLORADO BASIN			
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.							
1933-45	DEC-MAR	-.034	-	.072	-	-	-
	MAY-JUNE	-	-	-	-	-	-
	AUG-NOV	-	-	-	-	-	.161
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT							
1931-64	DEC-MAR	.033	-.010	-.049	-.012	-.056	.090
	MAY-JUNE	.061	-.022	-.070	-	-	-
	AUG-NOV	.042	-	-.064	-.014	-.041	.087
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT							
1951-82	DEC-MAR	-	-	-	-	-.134	.173
	MAY-JUNE	-.131	-	.213	.258	-	-.313
	AUG-NOV	-.077	-.024	.144	.312	-.432	.099
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH							
1928-46	DEC-MAR	-	-	-	.222	-.288	-
	MAY-JUNE	.069	-	-.058	-.044	-.387	.444
	AUG-NOV	.058	-	-.062	-	-	.143
				GREEN BASIN			
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.							
1951-62	DEC-MAR	-	-.066	.086	.044	-.204	.333
	MAY-JUNE	-	-.119	-	-	-	-
	AUG-NOV	-.065	-	.071	.058	-.259	.351
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO							
1950-82	DEC-MAR	-.045	.039	-	-.094	.377	-.273
	MAY-JUNE	-.074	-	.079	-	.269	-.317
	AUG-NOV	-	.018	-.033	-.126	.196	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT							
1950-79	DEC-MAR	.031	.022	-.107	-.201	-	.278
	MAY-JUNE	-.059	.029	-	-.106	.191	-
	AUG-NOV	-	.030	-.104	-.226	-	.246
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA							
1928-61	DEC-MAR	-	-	-	-.053	.033	.041
	MAY-JUNE	-	-.020	-	-.020	-	-
	AUG-NOV	-	-	-	-.054	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV							
1947-65	DEC-MAR	-	-	-	-	-	-
	MAY-JUNE	-	-	-	-	-	-
	AUG-NOV	-	-	-.174	-	-.210	.100

Table 9. — *Significant long-term trends in mass fraction (%/a) by linear regression* —Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				SAN JUAN BASIN			
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH							
1929-81	DEC-MAR	-.020	-	-	.034	-	-.039
	MAY-JUNE	.028	-.012	-	.029	-	-
	AUG-NOV	-.028	-	.031	.037	-.062	-
				LOWER COLORADO BASIN			
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.							
1927-81	DEC-MAR	.043	-.026	-.016	-	-.098	.059
	MAY-JUNE	.077	-.028	-.047	-	-.128	.124
	AUG-NOV	.071	-.027	-.081	-	-.133	.101
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,							
1925-61	DEC-MAR	.021	-.007	-.013	-	-.074	.055
	MAY-JUNE	.051	-.016	-.058	-.033	-.166	.175
	AUG-NOV	.031	-.007	-.043	-	-.100	.084

Table 10. — *Significant long-term trends in mass fraction (%/a) by log regression*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				UPPER COLORADO BASIN			
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.							
1933-45	DEC-MAR	-.033	-	.074	-	-	-
	MAY-JUNE	-	-	-	-	-	-
	AUG-NOV	-	-	-	-	-	.110
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT							
1931-64	DEC-MAR	.030	-.008	-.044	-.011	-.053	.084
	MAY-JUNE	.047	-.018	-.055	-	-	.082
	AUG-NOV	.038	-	-.055	-.012	-	.067
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT							
1951-82	DEC-MAR	-	-	-	-	-.146	.217
	MAY-JUNE	-.139	-	.096	-	-	-.446
	AUG-NOV	-.070	-.023	.127	.268	-.440	.214
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH							
1928-46	DEC-MAR	-	-	-	.215	-.301	-
	MAY-JUNE	.054	-	-	-	-.347	.384
	AUG-NOV	.051	-	-.054	-	-	.128
				GREEN BASIN			
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.							
1951-62	DEC-MAR	-	-.069	.082	.041	-.230	.310
	MAY-JUNE	-	-.125	-	-	-.305	.305
	AUG-NOV	-.073	-	.064	.053	-.258	.341
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.							
1950-82	DEC-MAR	-.047	.037	-	-.096	.334	-.268
	MAY-JUNE	-.085	-	.079	-	.263	-.319
	AUG-NOV	-	.016	-	-.122	.196	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT							
1950-79	DEC-MAR	.029	.021	-.111	-.218	-	.260
	MAY-JUNE	-	.030	-	-.133	.167	-
	AUG-NOV	-	.031	-.099	-.233	-	.233
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA							
1928-61	DEC-MAR	-	-	-	-.047	.032	.039
	MAY-JUNE	-	-.020	-	-.013	-	-
	AUG-NOV	-	-	-	-.043	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV							
1947-65	DEC-MAR	-	-	-	-	-	-
	MAY-JUNE	.061	-	-	-	-.275	.197
	AUG-NOV	-	-	-.201	-	-.214	.097

Table 10. — *Significant long-term trends in mass fraction (%/a) by log regression* — Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				SAN JUAN BASIN			
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH							
1929-61	DEC-MAR	-.020	-	-	.030	-	-.037
	MAY-JUNE	.028	-.011	-	.026	-	-
	AUG-NOV	-.023	-	.021	.031	-.081	-
				LOWER COLORADO BASIN			
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.							
1927-61	DEC-MAR	.032	-.021	-.012	-	-.079	.045
	MAY-JUNE	.064	-.022	-.043	-.021	-.121	.117
	AUG-NOV	.056	-.022	-.053	-	-.127	.092
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,							
1925-61	DEC-MAR	.018	-.006	-.013	-	-.070	.052
	MAY-JUNE	.049	-.015	-.059	-.034	-.169	.188
	AUG-NOV	.028	-	-.042	-	-.098	086

Table 11. — *Significant long-term trends in mass fraction (%/a) by semilog regression*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				UPPER COLORADO BASIN			
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.							
1933-45	DEC-MAR	-.036	-	.081	-	-	-
	MAY-JUNE	-	-	-	-	-	-
	AUG-NOV	-	-	-	-	-	.116
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT							
1931-64	DEC-MAR	.033	-.010	-.050	-.011	-.057	.091
	MAY-JUNE	.056	-.021	-.064	-	-	-
	AUG-NOV	.042	-.010	-.062	-.012	-	.075
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT							
1951-82	DEC-MAR	-	-	-	-	-.154	.230
	MAY-JUNE	-.147	-	.103	-	-	-.453
	AUG-NOV	-.072	-.024	.129	.278	-.458	.226
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH							
1928-46	DEC-MAR	-	-	-	.210	-.294	-
	MAY-JUNE	.050	-	-	-	-.335	.373
	AUG-NOV	.049	-	-.051	-	-	.122
				GREEN BASIN			
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.							
1951-62	DEC-MAR	-	-.070	.081	.041	-.240	.322
	MAY-JUNE	-	-.127	-	-	-.311	.311
	AUG-NOV	-.074	-	.065	.054	-.261	.348
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.							
1950-82	DEC-MAR	-.046	.037	-	-.098	.340	-.276
	MAY-JUNE	-.086	-	.079	-	.267	-.324
	AUG-NOV	-	.016	-.028	-.123	.195	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT							
1950-79	DEC-MAR	.029	.022	-.118	-.231	-	.269
	MAY-JUNE	-	.031	-	-.141	.173	-
	AUG-NOV	-	.032	-.107	-.244	-	.241
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA							
1928-61	DEC-MAR	-	-	-	-.049	-	.044
	MAY-JUNE	-	-.021	-	-.013	-	-
	AUG-NOV	-	-	-	-.046	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV							
1947-65	DEC-MAR	-	-	-	-	-	-
	MAY-JUNE	.062	-	-	-	-.273	.200
	AUG-NOV	-	-	-.205	-	-.221	.099

Table 11. — *Significant long-term trends in mass fraction (%/a) by semilog regression* —Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				SAN JUAN BASIN			
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH							
1929-61	DEC-MAR	-.020	-	-	.032	-	-.042
	MAY-JUNE	.028	-.012	-	.028	-	-
	AUG-NOV	-.024	-	.024	.033	-.081	-
				LOWER COLORADO BASIN			
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.							
1927-61	DEC-MAR	.041	-.027	-.016	-	-.098	.056
	MAY-JUNE	.083	-.030	-.056	-.026	-.157	.151
	AUG-NOV	.070	-.030	-.065	-	-.150	.103
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,							
1925-61	DEC-MAR	.019	-.007	-.012	-	-.074	.052
	MAY-JUNE	.051	-.016	-.059	-.033	-.170	.186
	AUG-NOV	.030	-.007	-.044	-	-.103	.085

Table 12. — *Significant long-term trends in mass fraction (%/a) with highest confidence levels of the different regressions*

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				UPPER COLORADO BASIN			
STATION 9095500 - COLORADO RIVER NEAR CAMEO, CO.							
1933-45	DEC-MAR	-.036	-	.074	-	-	-
	MAY-JUNE	-	-	-	-	-	-
	AUG-NOV	-	-	-	-	-	161
STATION 9152500 - GUNNISON RIVER NEAR GRAND JUNCT							
1931-64	DEC-MAR	.033	-.010	-.049	-.012	-.056	.090
	MAY-JUNE	.061	-.022	-.070	-	-	.082
	AUG-NOV	.042	-.010	-.064	-.014	-.041	.087
STATION 9180000 - DOLORES RIVER NEAR CISCO, UT							
1951-82	DEC-MAR	-	-	-	-	-.154	.173
	MAY-JUNE	-.147	-	.213	.258	-	-.446
	AUG-NOV	-.077	-.024	.144	.312	-.458	.226
STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH							
1928-46	DEC-MAR	-	-	-	.210	-.288	-
	MAY-JUNE	.069	-	-.058	-.044	-.335	.444
	AUG-NOV	.058	-	-.062	-	-	.128
				GREEN BASIN			
STATION 9217000 - GREEN R. NR GREEN RIVER, WYO.							
1951-62	DEC-MAR	-	-.066	.086	.044	-.240	.322
	MAY-JUNE	-	-.119	-	-	-.311	.311
	AUG-NOV	-.074	-	.071	.058	-.259	.351
STATION 9251000 - YAMPA RIVER NEAR MAYBELL, CO.							
1950-82	DEC-MAR	-.047	.039	-	-.098	.340	-.276
	MAY-JUNE	-.086	-	.079	-	.267	-.324
	AUG-NOV	-	.018	-.033	-.123	.196	-
STATION 9306500 - WHITE RIVER NEAR WATSON, UT							
1950-79	DEC-MAR	.031	.022	-.118	-.231	-	.269
	MAY-JUNE	-.059	.031	-	-.141	.191	-
	AUG-NOV	-	.030	-.107	-.244	-	.241
STATION 9315000 - GREEN RIVER AT GREEN RIVER, UTA							
1928-61	DEC-MAR	-	-	-	-.047	.032	.044
	MAY-JUNE	-	-.020	-	-.020	-	-
	AUG-NOV	-	-	-	-.043	-	-
STATION 9328500 - SAN RAFAEL RIVER NEAR GREEN RIV							
1947-65	DEC-MAR	-	-	-	-	-	-
	MAY-JUNE	.062	-	-	-	-.275	.200
	AUG-NOV	-	-	-.174	-	-.221	.099

Table 12. — *Significant long-term trends in mass fraction (%/a) with highest confidence levels of the different regressions* — Continued

PERIOD	SEASON	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARBONATE
				SAN JUAN BASIN			
STATION 9379500 - SAN JUAN RIVER NEAR BLUFF, UTAH							
1929-61	DEC-MAR	-.020	-	-	.032	-	-.042
	MAY-JUNE	.028	-.012	-	.028	-	-
	AUG-NOV	-.028	-	031	.033	-.081	-
				LOWER COLORADO BASIN			
STATION 9380000 - COLORADO R AT LEES FERRY, AZ.							
1927-61	DEC-MAR	.043	-.026	-.016	-	-.098	.059
	MAY-JUNE	.083	-.028	-.056	-.026	-.157	.151
	AUG-NOV	.070	-.030	-.065	-	-.150	.092
STATION 9402500 - COLORADO R. NEAR GRAND CANYON,							
1925-61	DEC-MAR	.021	-.007	-.013	-	-.074	.052
	MAY-JUNE	.049	-.016	-.059	-.034	-.169	.188
	AUG-NOV	.030	-.007	-.044	-	-.103	.086

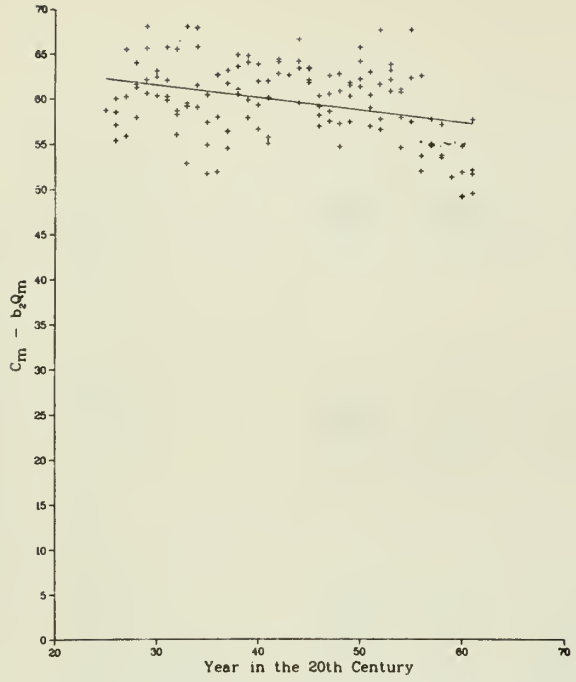

Figure 6. Linear trend of magnesium ion concentration with a linear correction for the variability of streamflow for the Colorado River near the Grand Canyon, December through March, 1925–61.

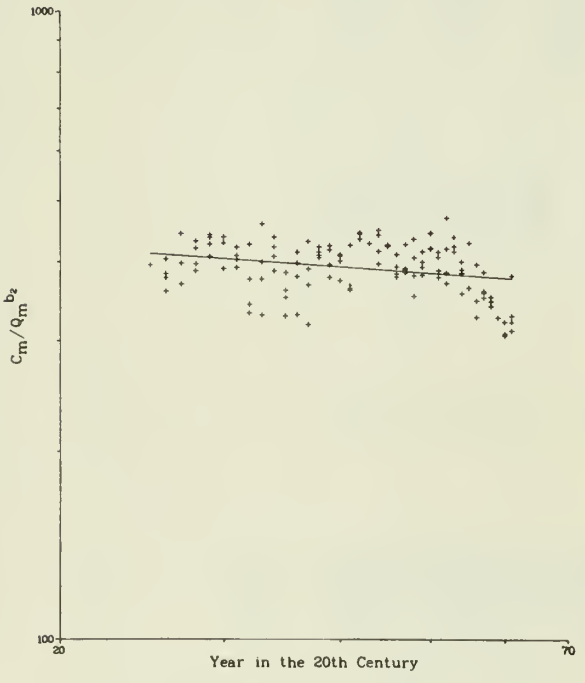

Figure 7. Log-log trend of magnesium ion concentration with a power correction for the variability of streamflow for the Colorado River near the Grand Canyon, December through March, 1925–61.

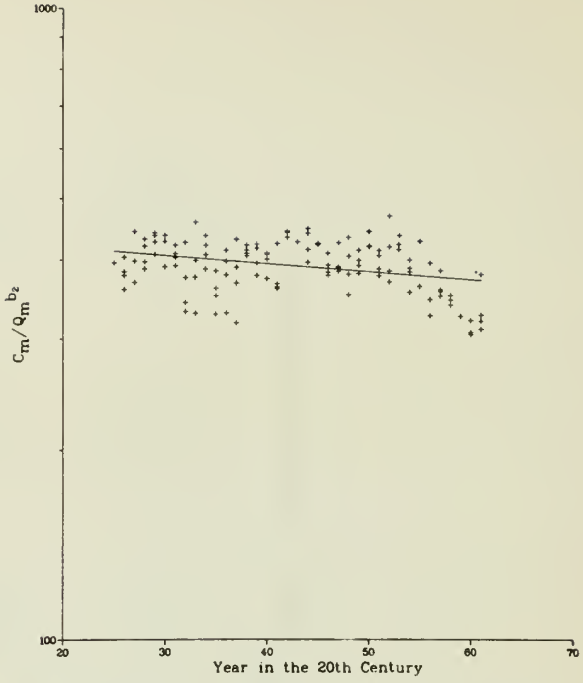

Figure 8. Semilog trend of magnesium ion concentration with a power correction for the variability of streamflow for the Colorado River near the Grand Canyon, December through March, 1925–61.

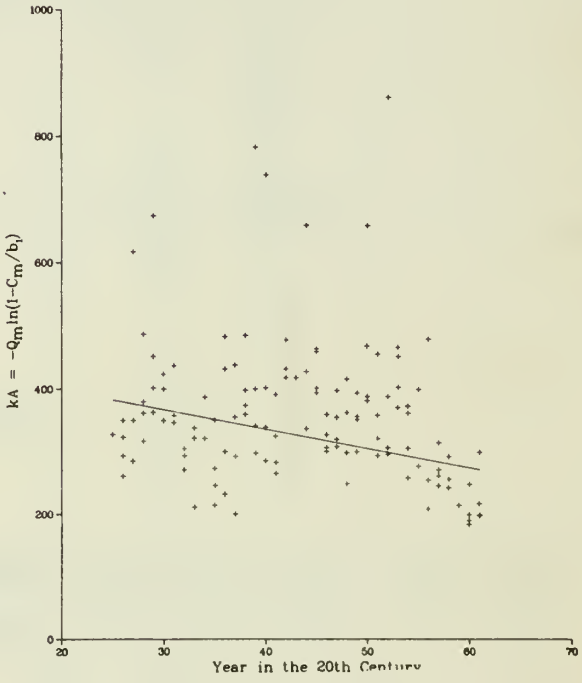

Figure 9. Magnesium ion concentration corrected for streamflow by the residence time equation. The ordinate is the product of the mass transfer coefficient (*k*) and the solid-liquid contact area (*A*) upstream of the gaging station on the Colorado River near the Grand Canyon, December through March, 1925–61.

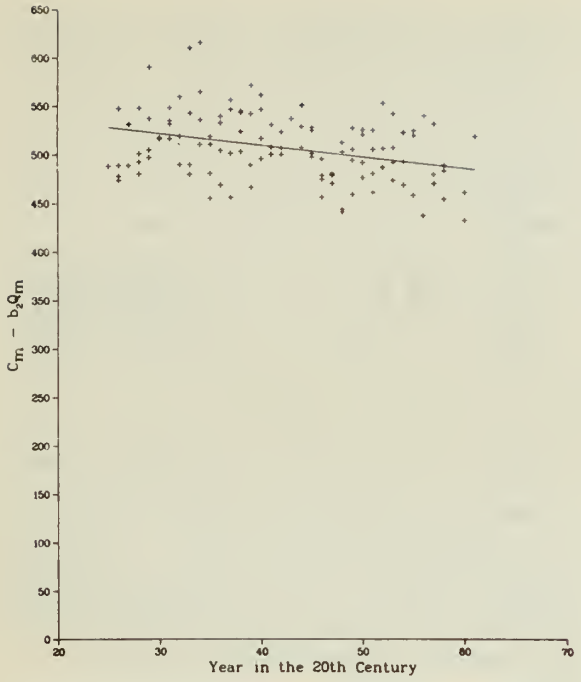

Figure 10. Linear trend of sulfate ion concentration with a linear correction for the variability of streamflow for the Colorado River near the Grand Canyon, December through March, 1925–61.

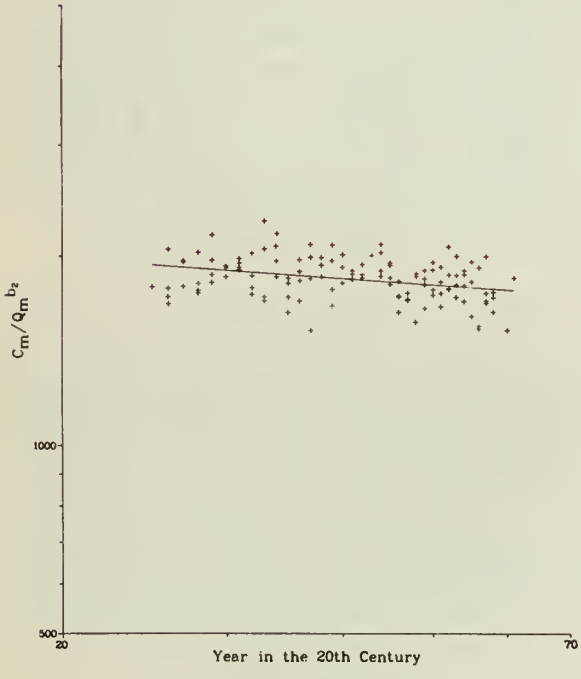

Figure 11. Log-log trend of sulfate ion concentration with a power correction for the variability of streamflow for the Colorado River near the Grand Canyon, December through March, 1925–61.

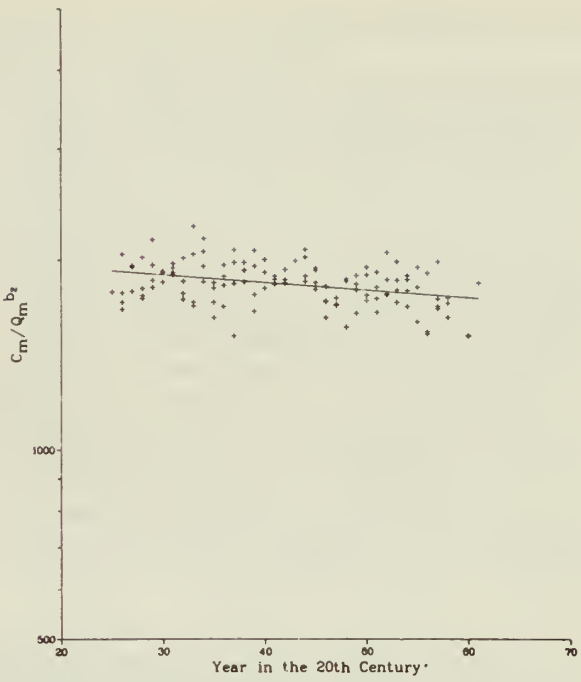

Figure 12. Semilog trend of sulfate ion concentration with a power correction for the variability of streamflow for the Colorado River near the Grand Canyon, December through March, 1925–61.

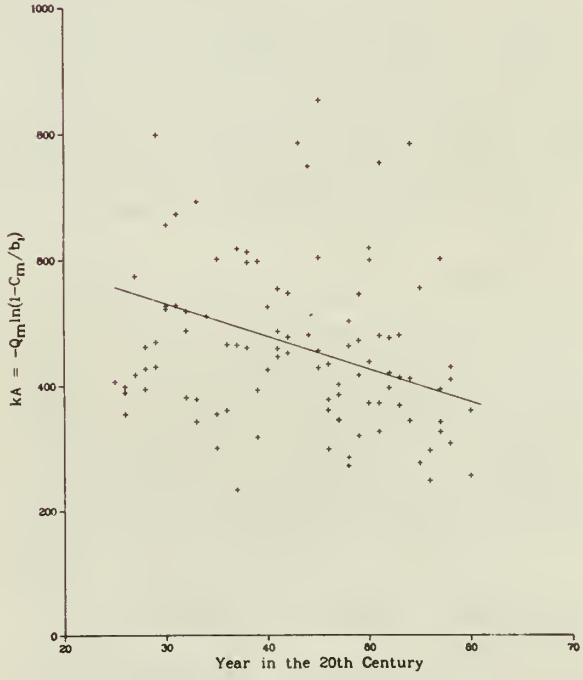

Figure 13. Sulfate ion concentration corrected for streamflow by the residence time equation. The ordinate is the product of the mass transfer coefficient (*k*) and the solid-liquid contact area (*A*) upstream of the gaging station on the Colorado River near the Grand Canyon, December through March, 1925–61.

Changes in Mean Values

Significant changes in concentration and mass fraction for selected stations are shown by season in tables 13 through 15. From 1963 through 1965, major reservoirs were created on the Gunnison and San Juan Rivers, on the Green River above Greendale, Wyoming, and on the Colorado River above Lees Ferry, Arizona. The obvious impact has been a general decrease in solute concentrations during months of historically low flow and high concentration (August–March) and an increase during what had been peak flow, low salinity months (May–June). This results from mixing waters of different quality in the reservoir, thereby reducing fluctuations. This effect was also confirmed by comparing the seasonal variation in pre–1963 with post–1965 mean values. An example showing sulfate concentration and mass fraction is given in table 16.

For all stations below new impoundments, the range of seasonal mean values is greatly reduced following flow regulation. This is most obvious for stations where flow is completely regulated. At Lees Ferry, the range of seasonal average sulfate concentrations was 103–447 mg/L before regulation and 225–257 mg/L after regulation. The range of sulfate mass fraction was reduced from 27–43 percent to 38–39 percent. A similar impact can be seen for the Greendale station. Smaller, but still significant, impacts are identified for the partially regulated stations: Grand Junction; Cisco; Green River, Utah; and Bluff. At unregulated stations (Maybell and Watson), the ranges increased or remained approximately constant.

Associated with the reduction in variability is a general shift in relative mass from sulfate to bicarbonate in August through March, and vice versa in May and June. The reduction in sulfate mass fraction can be attributed to the mixing in the reservoirs. Sulfate is more prevalent in base and return flows because its major source is dissolution of gypsum in ground water. Therefore, its dominance during these periods is reduced by mixing with the lower concentration spring runoff water. There was also a relative decrease in calcium during May and June. This may result from calcite precipitation within the reservoirs [8, 15].

Some of the impacts of impoundment can be traced downstream to the stations at Cisco and Green River, Utah. Generally, their magnitude and significance are somewhat reduced as intervening, unregulated inflow exerts a moderating effect. This is not true, however, for solute loads at Cisco. Figure 14 displays changes in streamflow and anion loads as they occur spatially throughout the basin. Note the decreased sulfate load at Cisco during the base and return flow periods. There does not seem to be any upstream source for either reduction. Streamflow has not changed significantly in the return flow season and has actually increased during base flow. The sulfate load has, therefore, decreased independently of flow, somewhere on the Colorado River between Cameo and Cisco. The most likely cause of this is a reduction in loading from agricultural sources in the Grand Valley near Grand Junction, Colorado. Here, also, gypsum dissolution is a major source of low flow sulfate load. The reduction in sulfate loading could be the result of two activities: (1) the salinity control practices initiated by the Soil Conservation Service in the mid–1970's, and (2) the urbanization of approximately 10 percent of the irrigated area. These activities involved lining laterals and farm ditches and reducing irrigation applications. Both activities could reduce subsurface return flow volume and salt pickup.

The changes identified for the station at Green River, Utah, cannot be attributed entirely to upstream impoundments. Here, also, water quality is affected by intervening inflows, particularly from the Yampa and White Rivers. Although neither of these tributaries is regulated, both exhibit significant changes in water quality. The concentrations and relative masses of sulfate and magnesium increased during all three seasons at the Yampa station. This may have resulted from surface coal mine development within the basin. Other investigators [6] have documented sulfate and magnesium loading from coal spoils in this area.

At the White River station, chloride and, to a lesser extent, sodium decreased in both concentration and relative mass; these decreases were most prominent during low flow seasons. These changes might have been caused by the plugging of Meeker Well, upstream of Meeker, Colorado, in 1968. This well was a point source of sodium-chloride contamination. It flowed at a regular rate, which was greatly reduced for 11 years after it was plugged. This flow reduction may explain the greater impact during low flow, when the well would have contributed a greater relative water volume to the river. These impacts can be traced downstream to the Green River, Utah station.

Downstream of the stations at Cisco; Green River, Utah, and Bluff, the waters of the Colorado, Green, and San Juan Rivers combine to form Lake Powell. Many of the same changes identified at these

Table 13. — *Significant differences in mean concentration and mass fraction ($P \leq 0.05$)* between the pre-1963 and the post-1965 periods, December–March*

Station	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate
			Upper Colorado Basin			
Gunnison R. near	-59	-31	-66	-9	-310	-52
Grand Junction	1	[1] (-)	-2	-	-6	7
Colorado R. near	-33	-19	-66	-41	-199	-31
Cisco	1	(-)	-1	2	-6	4
			Green Basin			
Green R. near	-	-	-19	-	-55	-
Greendale	-	-	-	-	-	2
Yampa R. near	-	6	-	-5	35	-
Maybell	1	1	-	-2	6	-4
White R. near	-5	-	-16	-22	-	-
Watson	-	1	-1	-3	-	4
Green R. at Green	-6	-4	-17	-17	-26	-11
River, Utah	(+)	-	-1	-2	-	2
			San Juan Basin			
San Juan R.	-31	-6	-25	-6	-117	-30
near Bluff	-	(+)	-	-	-3	3
			Lower Colorado Basin			
Colorado R. at	-38	-17	-65	-59	-165	-62
Lees Ferry	1	-	-1	-2	-	4
Colorado R. below	-7	3	12	-18	-	-
Hoover Dam	-1	(+)	1	2	-	-

* Upper value — concentration (mg/L), lower value — mass fraction (percent).
[1] (+) or (-) indicate a change of less than 0.5 percent.

three stations were also found at Lees Ferry, downstream of Glen Canyon Dam. However, the magnitude of these changes was generally greater than that which would have resulted from a simple combination of the changes upstream. Further downstream, at the Hoover Dam station, none of the impacts of upstream development can be identified. The two reservoirs, Lakes Powell and Mead, seem to have the major controlling influence on downstream water quality.

Impacts upstream of Lake Powell are apparently minor compared with the impact of the lake itself. This is clarified by comparing significant changes in the streamflow and solute loads throughout the basin (fig. 12). Changes in the load downstream of Lake Powell are generally an order of magnitude greater than those upstream. However, interpretation of these results is complicated by the concomitant large changes in streamflow. Storage in Lake Powell increased through most of the post-1965 period (the reservoir was not filled until 1980). Much of the reduction in solute load may be explained by the overall reduction in flow.

Equally difficult to explain are the increases in magnesium, sodium, and chloride concentrations identified at the station below Hoover Dam. These increases could be caused by the greater relative contribution of the Little Colorado River to the Lake Mead inflow during the filling of Lake Powell. Blue Springs, near the mouth of the Little Colorado, is a major source of sodium chloride loading and also contributes magnesium, calcium, and bicarbonate.

Table 14. — *Significant differences in mean concentration and mass fraction ($P \leq 0.05$)* between the pre-1963 and the post-1965 periods, May-June*

Station	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate
			Upper Colorado Basin			
Gunnison R. near	–	–	–	–	–	–
Grand Junction	-1	1	–	–	9	-8
Colorado R. near	–	5	–	17	–	–
Cisco	–	–	–	2	–	–
			Green Basin			
Green R. near	19	12	29	7	127	22
Greendale	-2	1	2	–	12	-13
Yampa R. near	–	3	–	–	15	–
Maybell	-2	1	–	–	4	-6
White R. near	–	–	–	–	–	–
Watson	–	1	–	-1	3	–
Green R. at Green	–	4	7	–	36	–
River, Utah	-2	1	1	–	7	-6
			San Juan Basin			
San Juan R.	11	7	15	5	77	17
near Bluff	-2	1	1	1	8	-8
			Lower Colorado Basin			
Colorado R. at	54	13	49	38	155	–
Lees Ferry	-3	[1] (+)	4	4	11	-16
Colorado R. below	-8	3	8	16	–	-6
Hoover Dam	-1	(+)	1	2	–	–

* Upper value — concentration (mg/L), lower value — mass fraction (percent).
[1] (+) or (–) indicate a change of less than 0.5 percent.

Increases in the concentration of the calcium and bicarbonate may have been offset by calcium carbonate precipitation in Lake Mead. The overall result would be the increased sodium and chloride concentrations and the somewhat smaller increase in magnesium, shown in tables 13 through 15.

Trends Following Regulation

Significant trends identified from linear regressions of the seasonal concentration, load, and mass fraction over time for the post-1965 period are listed in tables 17 through 19. Significant trends are far less common than significant changes following regulation. This suggests that the major impact of reservoirs on water quality occurs immediately. Where trends are identified for regulated stations, they are toward decreasing seasonal variability. This can be seen by comparing the trends in sulfate concentration and mass fraction from tables 17 through 19 with the post-1965 means shown in table 16. For example, the downward trends in concentration and mass fraction at Lees Ferry in May–June will, if they continue, reduce the range of seasonal averages in both cases. This correspondence also occurs for the Cisco station (concentration in December-March, mass fraction in December-March and August-November), the Green River Station (concentration and mass fraction in August-November), and the Hoover Station (concentration in December-March).

Decreasing trends in the concentration and load of sodium and chloride on the White River and the

Table 15. — *Significant differences in mean concentration and mass fraction ($P \leq 0.05$)* between the pre-1963 and the post-1965 periods, August-November*

Station	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate
			Upper Colorado Basin			
Gunnison R. near	-54	-26	-66	-8	-295	-
Grand Junction	1	-	-2	-	-3	4
Colorado R. near	-24	-17	-41	-	-188	-
Cisco	1	[1] (-)	-	3	-6	3
			Green Basin			
Green R. near	-	-	-	-	-	-
Greendale	-	(+)	-1	-	-	-
Yampa R. near	-	2	-	-	21	-
Maybell	-	(+)	-	-2	4	-
White R. near	-9	-	-	-22	-	-
Watson	-	1	-	-3	-	3
Green R. at Green	-	-	-7	-11	-	-
River, Utah	-	(+)	-1	-1	2	-
			San Juan Basin			
San Juan R.	-18	-	-	-	-67	-
near Bluff	-	0.3	-	-	-	2.8
			Lower Colorado Basin			
Colorado R. at	-29	-18	-61	-39	-223	-55
Lees Ferry	-	-	-	-	-5	6
Colorado R. below	-7	2	9	15	-	-
Hoover Dam	-1	(+)	1	2	-	-

* Upper value — concentration (mg/L), lower value — mass fraction (percent).
[1] (+) or (-) indicate a change of less than 0.5 percent.

concentration, load, and mass fraction of sulfate at Cisco may be associated with salinity control activities, which were discussed in the previous section.

Most of the increasing trends were for loads at Lees Ferry during the May-June season. These were associated with an increasing trend in streamflow, the only flow trend identified. Because no solute concentration trends were found, the flow trend is probably the primary reason for the increasing loads. Overall, the impacts of reservoir storage are easily identifiable using the two selected statistical tests. Other activities influencing water quality in the basin were also found. However, the reservoirs, especially Lakes Powell and Mead, appear to exert major control on the quality of the inflow to the lower basin.

CONCLUSIONS

1. A procedure was proposed and FORTRAN programs were developed for computing monthly values for streamflow, concentrations of six major ions, and concentration of the sum of these six ions. This procedure was based on USGS WATSTORE data of daily flows, daily specific conductance, and approximately monthly chemical analyses. Monthly values were generated for 15 gaging stations in the Colorado River Basin after deletion of obviously erroneous WATSTORE data and identification of suspected erroneous data. The resultant computer files provide an easily accessible historical record of flow and salinity, which can be used in statistical analyses by Government, academic, and private researchers.

Table 16. — *Comparison by season of the pre-1963 and the post-1965 sulfate concentrations and mass fractions*

Station	Mean concentration (mg/L)						Mean mass fraction (percent)					
	pre-1963			post-1965			pre-1963			post-1965		
	D-M	M-J	A-N[1]	D-M	M-J	A-N	D-M	M-J	A-N	D-M	M-J	A-N
Gunnison R. near Grand Junction	632	175	854	*321	280	*560	53	37	56	*46	*46	*52
Colorado R. near Cisco	473	119	616	*274	160	*428	39	30	45	*33	32	*40
Green R. near Greendale	273	98	209	*218	*225	226	39	26	38	*33	32	*40
Yampa R. near Maybell	88	19	70	*122	*34	*91	22	15	20	*29	*19	*23
White R. near Watson	206	76	191	189	82	183	29	20	28	29	*23	29
Green R. at Green River, Utah	300	80	286	*275	*116	*297	38	23	38	38	*30	*40
San Juan R. near Bluff	391	90	367	*274	*167	*299	46	30	45	*43	*38	43
Colorado R. at Lees Ferry	409	103	447	*244	*257	*225	39	27	43	38	*39	*38
Colorado R. below Hoover Dam	291	300	293	296	294	290	40	40	40	39	39	39

* Indicates significant difference ($P \leq 0.05$).
[1] D-M = December-March
M-J = May-June
A-N = August-November

Table 17. — *Significant trends in the post-1965 period, December-March*

Station	Flow m^3/s	Linear trend slope, a^{-1} ($P \leq 0.05$)* Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate
		Upper Colorado Basin					
Gunnison R. near Grand Junction	–	–	–	-2.66	-0.51	–	–
		–	–	–	–	–	–
		0.07	-0.02	-0.08	–	–	–
Colorado R. near Cisco	–	–	-0.64	–	–	-5.77	–
		–	-0.05	-0.13	–	-0.40	–
		–	-0.03	–	–	-0.25	0.22
		Green Basin					
Green R. near Greendale	–	–	–	–	-0.35	–	0.79
		–	–	–	–	–	–
		–	–	–	-0.07	–	–
Yampa R. near Maybell	–	–	–	–	–	–	–
		–	–	–	–	–	–
		–	–	–	–	–	–
White R. near Watson	–	–	–	-3.34	-3.68	–	–
		-0.04	–	-0.06	-0.06	-0.09	–
		–	–	–	–	–	–
Green R. at Green River, Utah	–	–	–	–	-0.54	–	1.54
		–	–	–	-0.06	–	–
		–	–	-0.07	-0.07	–	0.25
		San Juan Basin					
San Juan R. near Bluff	–	–	–	–	–	–	–
		–	–	–	–	–	–
		–	–	–	–	–	–
		Lower Colorado Basin					
Colorado R. at Lees Ferry	–	-0.89	–	–	–	–	-1.16
		–	–	–	–	–	–
		-0.04	0.02	–	–	–	–
Colorado R. below Hoover Dam	–	-0.61	–	-0.82	–	-2.25	–
		–	–	–	–	–	–
		–	–	–	–	-0.07	–

* Upper value — concentration (mg/L)
middle value — load (kg/s)
lower value — mass fraction (percent).

After the proposed procedure is reviewed, modified, and approved, the data files will provide a common basis for the evaluation of salinity relationships in the Colorado River Basin. Therefore, discussions of differing statistical results regarding salinity relationships will center on differences in the analyses themselves and not on differences in the data.

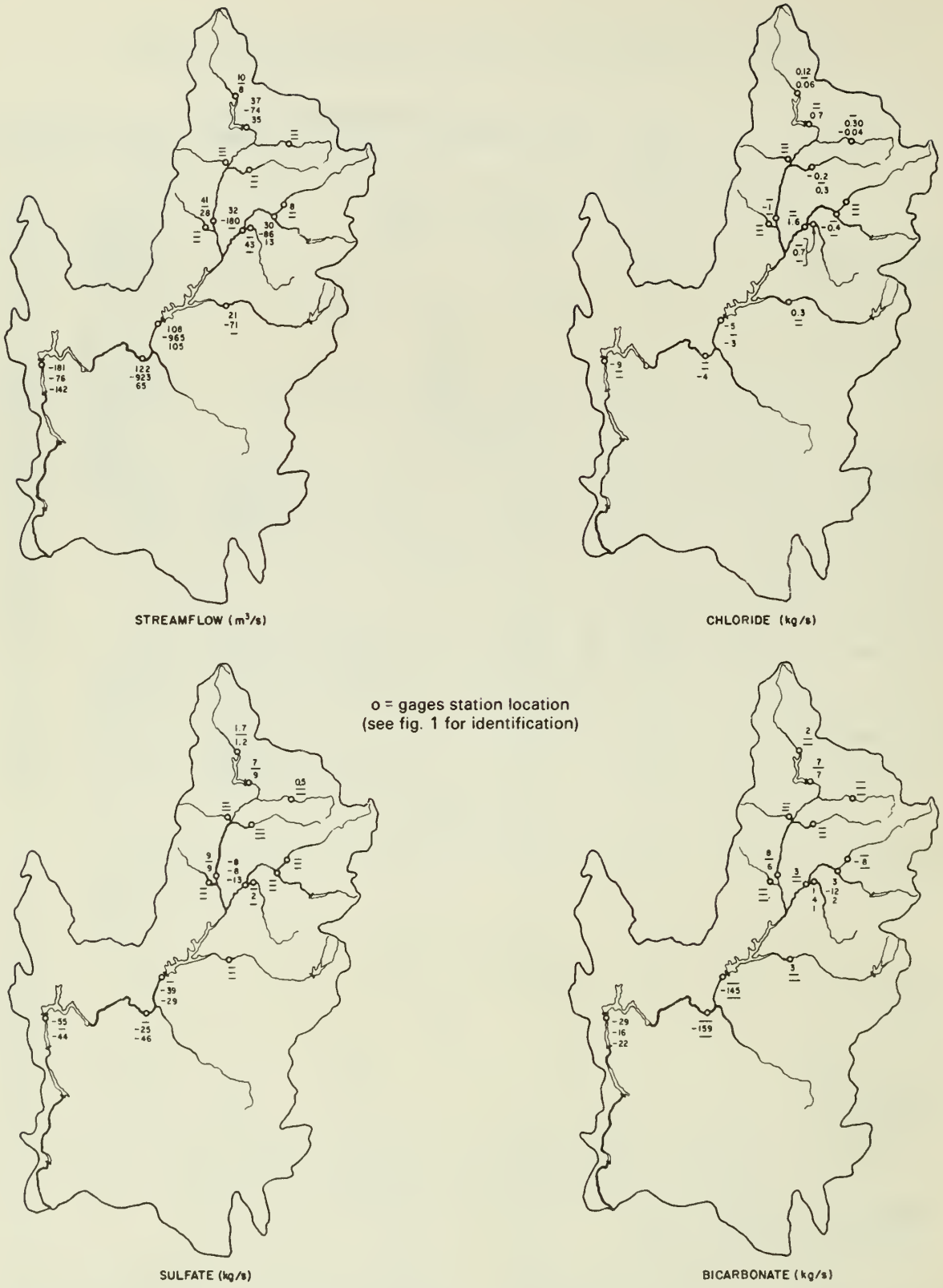

Figure 14. — Significant differences ($P \leq 0.05$) in streamflow (m^3/s) and anion loads (kg/s) between the pre-1963 and the post-1965 periods. Upper value: December–March, middle value: May–June, lower value: August–November.

Table 18. — *Significant trends in the post-1965 period, May-June*

Station	Linear trend slope, a^{-1} ($P \leq 0.05$)*						
	Flow m^3/s	Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate
Upper Colorado Basin							
Gunnison R. near Grand Junction	–	–	–	–	–	–	–
		–	–	–	–	–	–
		–	–	–	–	–	–
Colorado R. near Cisco	–	–	–	–	–	–	–
		–	–	–	–	–	–
		–	–0.07	–	–	–	–
Green Basin							
Green R. near Greendale	–	–	–0.39	–	–0.41	–	–
		–	–	–	–	–	–
		–	–0.03	–	–0.05	–	0.17
Yampa R. near Maybell	–	–	–	–	–	–	–
		–	–	–	–	–	–
		–	–	–	–	0.40	–
White R. near Watson	–	–	–	–	–	–	–
		–	–	–	–0.05	–	–
		–	–	–	–0.30	–	–
Green R. at Green River, Utah	–	–	–	–	–	–	–
		–	–	–	–0.14	–	–
		–	–	–	–	–	–
San Juan Basin							
San Juan R. near Bluff	–	–	–	–	–	–	–
		–	–	–	–0.14	–	–
		–	–	–	–	–	–
Lower Colorado Basin							
Colorado R. at Lees Ferry	–	–1.07	–	–	–	–2.90	–
		–0.91	–	–	–	–2.81	–
		–0.06	–	–	–	–0.10	–
Colorado R. below Hoover Dam	–	–0.48	–0.19	–0.80	–	–	–
		–	–	–	–	–	–
		–	–	–	–	–	–

* Upper value — concentration (mg/L)
middle value — load (kg/s)
lower value — mass fraction (percent).

Based on the monthly values of concentrations and streamflow, the annual cycle appears to have three distinct seasons: baseflow (December–March), peak runoff (May-June), and return flow (August-November).

2. A theoretical residence time model for describing the concentration-streamflow relationship at each station with unregulated flows was derived and compared with the widely used power model. For monthly values of concentration and stream-

Table 19. — *Significant trends in the post-1965 period, August-November*

Station	Flow m^3/s	Linear trend slope, a^{-1} ($P \leq 0.05$)* Calcium	Magnesium	Sodium	Chloride	Sulfate	Bicarbonate
Upper Colorado Basin							
Gunnison R. near	–	–	–	-0.10	–	–	–
Grand Junction		–	-0.06	–	–	-0.44	–
		0.09	-0.02	-0.07	–	–	–
Colorado R. near	–	–	–	–	–	–	–
Cisco		–	–	–	–	-0.53	–
		–	–	–	-0.13	-0.27	–
Upper Green Basin							
Green R. near	–	–	-0.32	–	-0.26	–	–
Greendale		–	–	–	–	–	–
		–	–	–	–	–	–
Yampa R. near	–	–	–	–	–	–	–
Maybell		–	-0.01	-0.01	-0.01	–	–
		–	–	–	–	–	–
White R. near	–	–	–	–	–	–	–
Watson		–	–	-0.03	-0.03	–	–
		–	–	–	–	–	–
Green R. at Green	–	-0.66	-0.33	-0.70	–	-3.09	–
River, Utah		–	–	–	–	–	–
		–	–	–	–	-0.15	-0.20
San Juan Basin							
San Juan R.	–	-2.33	–	–	–	–	-3.42
near Bluff		–	–	-0.15	–	-0.52	–
		–	–	–	–	–	–
Lower Colorado Basin							
Colorado R. at	9.85	–	–	–	–	–	–
Lees Ferry		0.59	0.26	0.73	0.55	2.28	1.41
		-0.04	–	–	–	–	–
Colorado R. below	–	-0.56	–	–	–	–	-0.89
Hoover Dam		–	–	–	–	–	–
		–	–	–	–	–	–

* Upper value — concentration (mg/L)
middle value — load (kg/s)
lower value — mass fraction (percent).

flow, the models describe the relationship equally well, and both can be used to correct for the variability of streamflow in evaluating the statistical significance of long-term changes in concentration.

The relationships between the solute concentrations and the streamflow vary with the solute, season, and gaging station. The bicarbonate ion concentration is relatively independent of the streamflow for all stations. Because the concentration–streamflow relationship varies from solute to solute, TDS–streamflow equations may be less accurate than equations for individual solutes.

3. Long-term trends in solute concentrations for 12 gaging stations were evaluated for statistical significance by three empirical equations with multiple linear regressions and by the residence time equation with a nonlinear regression. These four equations yielded similar results and are, therefore, corroborative.

Long-term trends in solute loads can be estimated from the regression results for concentrations. With a linear streamflow term in the regression, this procedure is preferable to direct regressions with solute loads because upstream diversions have a smaller effect on the estimated trends. With a power streamflow term, both procedures yield identical results, making load regressions redundant.

Long-term trends in solute mass fractions for 12 gaging stations were evaluated for statistical significance by three empirical equations with multiple linear regression. As expected, mass fraction is the least sensitive to variability of streamflow, so that both the linear and power corrections for streamflow were satisfactory. The results from the three equations were almost identical. These results agreed with the estimated trends in concentration, but yielded no new information.

Before construction of the major upstream dams, the concentrations of magnesium, sodium, and sulfate ions during the baseflow season of December–March decreased in stoichiometric proportions, resulting in a reduction of approximately 2 mg/L per year in the baseflow TDS of the Colorado River at Lees Ferry and at the Grand Canyon. At the Grand Canyon from 1925–61: the annual magnesium load decreased at an average rate of 0.4 percent per year (2×10^6 kg/a), the sodium and sulfate loads decreased 0.3 percent per year (5×10^6 and 12×10^6 kg/a), the calcium load increased by 0.4 percent per year (5×10^6 kg/a), and the bicarbonate load increased by 0.7 percent per year (21×10^6 kg/a). No statistically significant changes in the chloride load are evident.

4. After construction of the Colorado River Storage Project reservoirs in the early 1960's, the variability of solute concentrations and mass fractions were reduced at many downstream gaging stations. The degree of reduction was relatively proportional to the degree of regulation. At some sites, trends toward further reduction in variability developed after the initial reservoir filling. Several other activities of man, including mining, urbanization, and salinity control practices, may have affected the water quality in the basin. Impacts decreased with distance downstream, but were often identified at more than one gaging station. However, the major reservoirs, Lakes Powell and Mead, masked all impacts occurring in the Upper Basin.

No significant trends in the load for any solute have been identified for the station below Hoover Dam since 1965; however, the concentration of all solutes except chloride decreased in at least one season.

IMPLICATIONS FOR THE SALINITY CONTROL PROGRAM

The development of a standard data base for salinity at the major gaging stations in the Colorado River Basin will benefit researchers evaluating the salinity problem and potential measures for salinity control. The present work indicates that standard statistical procedures applied to these data are sensitive enough to identify impacts of the magnitude projected for proposed USBR salinity control projects. However, it also shows the overriding influence of Lakes Powell and Mead on salinity in the Colorado River downstream of Hoover Dam. More research is needed to understand the processes occurring within these reservoirs to assess the probable impact of the Upper Basin projects on Lower Basin water quality.

Salinity downstream of Lake Mead was found to be relatively stable, with some recent decreases in concentration. Therefore, the observed changes further downstream at Imperial Dam may have been caused by changing conditions in the Lower Basin area. Additional studies are needed to identify their sources.

RECOMMENDATIONS FOR FURTHER RESEARCH

After a review and any necessary revisions, the data base development technique should be applied to other major stations in the basin, particularly stations on the Colorado River below Parker Dam and at Imperial Dam. In addition, the existing data base should be updated as new data become available. Potential modifications to the technique include increasing the period of interpolation for chemical analyses, particularly for stations with regulated flow, where the chemical variability is small. This would extend the period of record at sites where the USGS has gone to 2-month or quarter-year sampling intervals.

Additional statistical analyses are suggested using this expanded data set. Seasonal division of the data for stations downstream of major impoundments is not necessary because of their reduced variability. Regression analyses should be conducted only for concentration, with meq/L as the preferred units. This would facilitate the identification of chemical relationships in significant changes and trends. Differences in the load between consecutive, unregulated stations should also be analyzed to identify impacts such as those hypothesized for the Grand Valley area.

The greatest need is for a more complete investigation of the potential sources of identified changes and trends. Statistical results should receive a multi-disciplinary review to determine sources. If possible, data should be collected to confirm suspected sources. The probable impact of USBR salinity control projects can then be evaluated.

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APPENDIX A

USER'S GUIDE TO THE MONTHLY DATA GENERATION PROCEDURE

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GENERATION OF MONTHLY AVERAGE STREAMFLOW AND CONCENTRATION VALUES

A series of FORTRAN computer programs was developed to check data retrieved from the USGS WATSTORE data base and then to use these data to generate average monthly values for discharge and constituent concentrations. These programs are described below in the order of their application to a particular set of retrieved data. Also described is the iterative procedure used to identify possible errors in the WATSTORE data. The programs are stored on the USBR CYBER under User No. ER1000D. Catalog names are identical to program names.

Modifications made to the WATSTORE data before generating monthly values are tabulated for the appropriate station in table 2 of appendixes B through P. The responsible USGS district offices are notified of discrepancies between WATSTORE data and published Water Supply Paper values.

Step 1 — WATSTORE Data Retrieval

Data were transferred from the USGS computer system in Reston, Virginia, to the USBR CYBER by an automatic communication link developed by Main [1]*. Three retrievals were required for each station: (1) daily value streamflow, (2) daily value specific conductance, and (3) periodic water quality. Specific conductance retrievals included both random daily measurements (statistic code 11) and mean daily values (statistic code 3). The latter are available only for stations with continuous recorders. Water quality parameters retrieved were calcium (code 915), magnesium (code 925), sodium (codes 930), sodium plus potassium (code 933), chloride (code 940), sulfate (code 945), bicarbonate (code 440, 90440, 95440, and 99440), alkalinity (codes 410, 90410), specific conductance (code 95), and TDS (total dissolved solids) as evaporation residues at 180 °F (code 70300). In all cases the entire period of record was retrieved.

Step 2 — Water Quality Inventory

The water quality data file can be inventoried using program QWTAB1. Output from this program gives the period of record, number of samples, and range of values for each parameter in the file (fig. A-1). Values which appear too extreme can be located in the data file, checked against the appropriate water supply paper, and corrected, if necessary. In this and all subsequent programs, a zero water quality value is considered missing data.

The inventory is generated from an interactive terminal using the following commands:

```
BAT
GET, QWTAB1, data file
FTN, I = QWTAB1, L = 0
LGO, data file
```

where "data file" is the catalog name of a WATSTORE water quality data file. Output will be displayed on the terminal. A separate output file on TAPE4 lists duplicate and overlapping dates. This list can be displayed on the terminal by entering:

```
REWIND, TAPE4
LIST,F=TAPE4
```

Step 3 — TDS and Conductivity Regressions

Three programs (REGWQ1, REGWQ2, and REGWQ3) are used to regress the sum of six solutes against the evaporation residue TDS and to determine the empirical constant in the relationship between the observed and computed specific conductance.

The first program (REGWQ1) reads the WATSTORE data and computes the dependent and independent regression variables for all samples with sufficient data. If sodium concentration (code 930) is missing, sodium plus potassium data (code 933) are used. If bicarbonate concentration is missing, it is computed from alkalinity:

$$\text{Bicarbonate} = \text{alkalinity}/0.8202$$

This is simply the mass ratio between bicarbonate (HCO_3) and calcium carbonate ($CaCO_3$) in the stoichiometric relationship:

$$CaCO_{3(s)} + H_2O + CO_{2(g)} \rightleftharpoons 2HCO_3^{-1} + Ca^{+2}$$

The conversion is made under the assumption that the total alkalinity (as $CaCO_3$) results from bicarbonate. This assumption is reasonable for water with pH less than 8.3 [2]. Because bicarbonate and alkalinity analyses in WATSTORE are specified

* Numbers in brackets refer to entries in the bibliography.

83/08/03. WATER QUALITY DATA FILE INVENTORY 15.42.40.
FOR
STATION - 9180500
COLORADO RIVER NEAR CISCO UTAH

	PARMETER ID	CODE	FIRST DATE	LAST DATE	NO.OF ITEMS	MINIMUM	MAXIMUM	MEAN	NO.OF FLAGD ITEMS
1.	ALK(F)	410	2810	8009	1237	80.00	221.00	152.97	0
2.	HCO3(U)	440	2810	8006	1345	97.00	270.00	185.43	0
3.	CA	915	2810	8305	1304	36.00	265.00	111.57	0
4.	MG	925	2810	8305	1303	6.30	131.00	44.70	0
5.	NA	930	2810	8305	1154	15.00	495.00	158.22	0
6.	CL	940	2810	8305	1374	8.00	695.00	139.43	0
7.	SO4	945	2810	8305	1371	52.00	1320.00	430.36	0
8.	SC	95	3510	8305	1363	330.00	4049.99	1442.13	0
9.	TDS(R)	70300	3510	8304	976	208.00	2350.00	972.13	0
10.	NA+K	933	4310	8002	208	21.00	298.00	127.32	0
11.	ALK(L)	90410	8010	8305	24	83.00	180.00	141.96	0

Figure A-1. — Example output from program QWTAB1

from several sources, the determination is attempted in the following order: (1) bicarbonate, titration to pH 4.5, lab (parameter code 95440), (2) bicarbonate, unspecified (code 440), (3) bicarbonate, incremental titration, lab (code 90440), (4) alkalinity, titration to pH 4.5, lab (code 90410), (5) bicarbonate, incremental titration, field (code 99440), and (6) alkalinity, titration to pH 4.5, field (code 410). In the study area, only sources (2), (4), and (6) are generally available.

To compare the sum of six solutes with evaporation residue TDS, the residue TDS must be increased to account for bicarbonate lost during evaporation at 180 °F:

$$2HCO_3 + \text{heat} \rightleftharpoons CO_3^{-2} + H_2O_{(g)} + CO_{2(g)}$$

According to the mass ratio of CO_3^{-2} to $2HCO_3^-$, 50.83 percent of the bicarbonate is lost. Therefore, the regression equation is

$$\text{sum} = a + b\left\{TDS_{(\text{residue})} + 0.5083\ (HCO_3)\right\}$$

The sum of six solutes (sum) and the adjusted TDS are computed by program REGWQ1 for each complete analysis. Regression parameters a and b are evaluated using program REGWQ2. Expected values of TDS regression coefficients are a slope (b) of approximately 1 and a slightly negative intercept (a). This accounts for constituents, mainly silica and potassium, included in the evaporation residue but not in the sum of major ions.

Specific conductance (L) can be estimated from the equivalent ionic conductances using the method of Tanji and Biggar [3]:

$$L = \sum_i (\lambda^\circ_i - \alpha C_i^{0.5})\, C_i$$

where: λ°_i = Limiting ionic conductance of species i
C_i = Molar concentration of species i
α = An empirical constant

Equation 5 may be rearranged:

$$\sum(\lambda^\circ_i C_i) - L = \alpha C^{1.5}$$

or:

$$y = \alpha x$$

REGWQ1 computes the variable (x and y) terms for each complete analysis in the WATSTORE water quality data file. The constant α is then evaluated using linear regression forced through the origin (program REGWQ2). The normal range of values for α is 5–10.

Linear regressions are computed using SPSS procedures [4]. Program REGWQ2 contains the SPSS directives to produce line-printer scatter diagrams of the data (output from REGWQ1) and the linear regression coefficients. Examples are shown in figures A-2 and A-3.

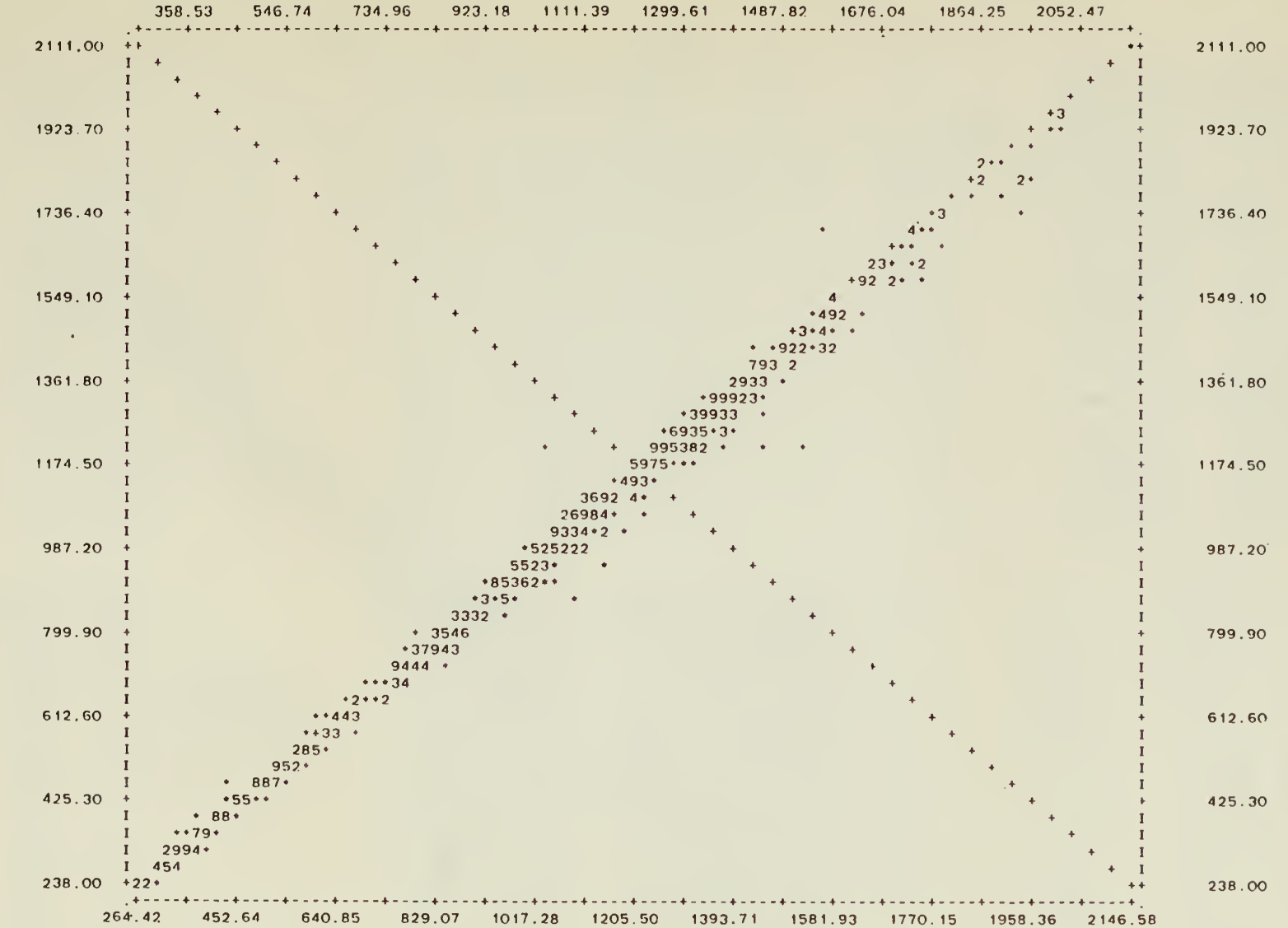
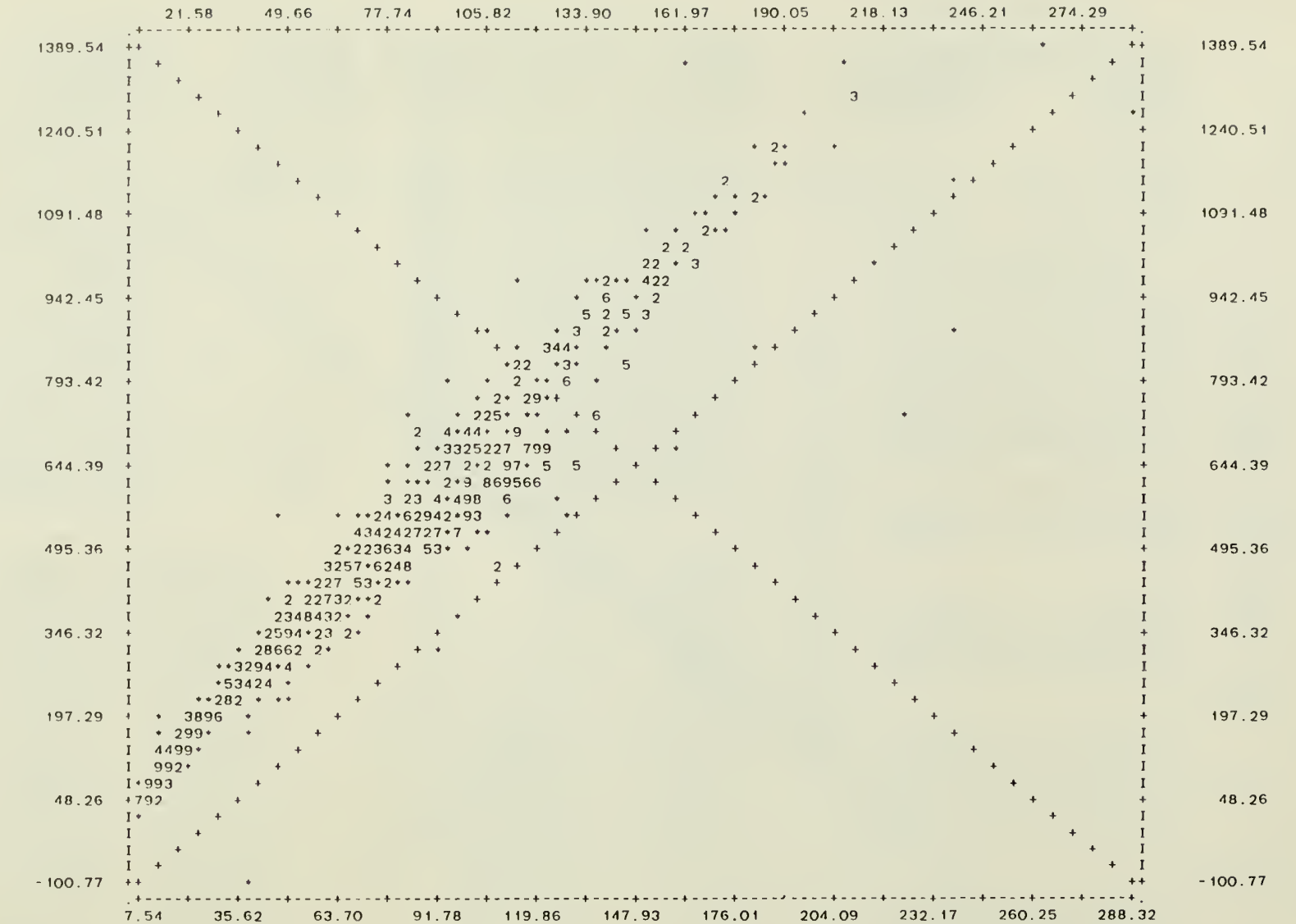


Figure A-2. — Example output from regression of sum of solutes on adjusted residue TDS.

STATISTICS..

CORRELATION (R) -	.99756	R SQUARED -	.99512	SIGNIFICANCE R -	.00001
STD ERR OF EST -	28.21112	INTERCEPT (A) -	-13.86671	STD ERROR OF A -	2.69442
SIGNIFICANCE A -	.00001	SLOPE (B) -	.97559	STD ERROR OF B -	.00233
SIGNIFICANCE B -	.00001				

PLOTTED VALUES - 858 EXCLUDED VALUES - 0 MISSING VALUES - 442



VARIABLE	B	STD ERROR B	F SIGNIFICANCE	BETA ELASTICITY	VARIABLE	PARTIAL	TOLERANCE	F SIGNIFICANCE
XSC	6.2756324	.25465763E-01	60729.764 0	.9917868 .97401				

ALL VARIABLES ARE IN THE EQUATION.

Figure A-3. — Example output from regression evaluation of conductance constant α.

By inspection of the scatter diagrams, obvious data problems can be identified. These are located in the data file, checked against Water Supply Papers and corrected. Final regression coefficients are used in later programs.

The third program (REGWQ3) is the Batch JCL (job control language), which runs the other two. Before submission, it must be edited to access the desired water quality input file and create the desired output file. The program is then run, using the commands:

```
OLD, REGWQ3
SUB
```

A dayfile, which includes cost information, will be saved under the name DFRTDS.

Step 4 — Regression of Conductivity Versus Streamflow

The daily value data for specific conductance (L) and streamflow (Q) are also checked by regression. As in step 3, a series of programs is used. REGSC1 reads data from the two files, sorts them by date, and transforms them to natural logarithms. Only dates with both an L and Q value are used in the regression. REGSC2 is the SPSS directive file. It produces a scatter diagram and regression statistics (fig. A–4). REGSC3 is the CYBER job control file that executes the other two.

To run the procedure, REGSC3 must be edited to access the desired data files. An output file name can also be specified. From an interactive terminal, enter the following commands:

```
OLD, REGSC3
(edit)
SUB
```

Output will be sorted in the specified file. A dayfile will also be created under the name DFRSC.

The scatter diagram can be used to identify outliers, which may be data entry errors. The dates of outliers and extreme values can be listed using program CHKSC. CHKSC is run in BATCH mode using the FTN and LGO commands. Before it is run, the program must be edited to specify the standard error of estimate from REGSC3 output. Also, the user must set the ranges of specific conductance and streamflow, outside which extreme values and dates will be listed.

The REGSC3 output is also used to find the slope of the log-log relationship between L and Q. This slope is identical to the exponent, B, in the relationship:

$$L = aQ^B$$

The fitted exponent is used in step 6 to determine the weighting factor for interpolation of missing conductance data.

Step 5 — Tabulation of Water Quality Data

The WATSTORE water quality data file is reformatted in a readable table by program QWTAB2. If necessary, bicarbonate and sodium values are determined as described in step 2. Single missing concentrations within any individual sample are then estimated assuming a charge balance of zero. Estimates are constrained to values within the observed range for that constituent. If two or more values are missing from a single analysis, no estimation is attempted.

QWTAB2 also checks the estimates of sum of constituents from residue TDS, the calculation of specific conductance from individual ionic equivalent values, and the charge balance. The TDS and conductance estimates are made using the regression coefficients evaluated in step 3. The charge balance is computed using the following factors to convert concentrations from mg/L to meq/L:

Constituent	*Factor*
Calcium	20.04
Magnesium	12.15
Sodium	22.99
Chloride	35.45
Sulfate	48.03
Bicarbonate	61.02

A partial listing of the output table is shown in figure A–5.

A separate table (fig. A–6) gives error statistics for the computed TDS, specific conductance, and net charge.

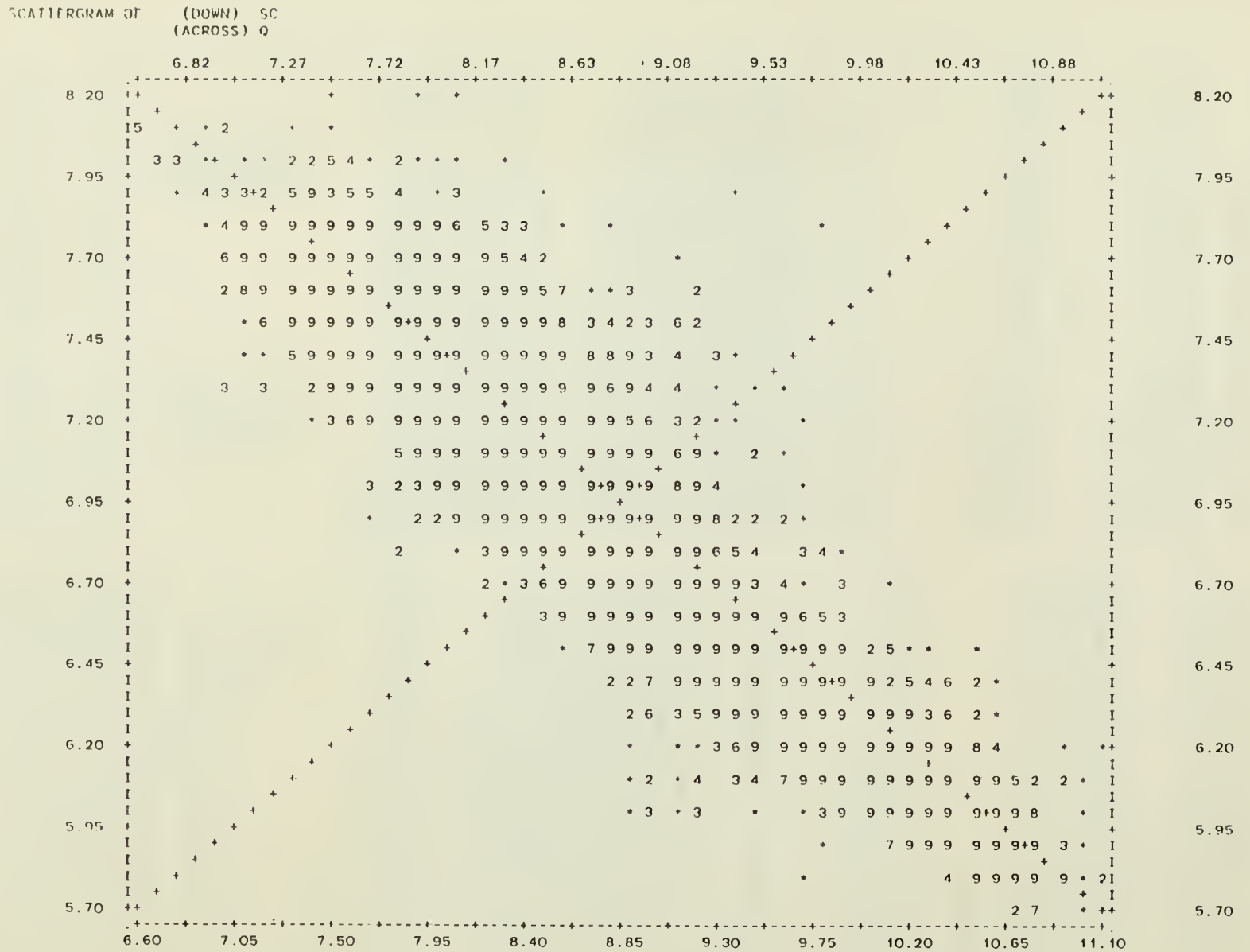


Figure A-4. — Example output from log-log regression of daily value conductance on streamflow.

STATISTICS..

CORRELATION (R) -	-.93521	R SQUARED -	.87462	SIGNIFICANCE R -	.00001
STD ERR OF EST -	.17749	INTERCEPT (A) -	12.07670	STD ERROR OF A -	.01542
SIGNIFICANCE A -	.00001	SLOPE (B) -	-.58752	STD ERROR OF B -	.00181
SIGNIFICANCE B -	.00001				

Deviations between observed and estimated values are accumulated and used to compute two error statistics, RMSE (root-mean-square error) and NME (normalized mean error):

$$RMSE = \left[\frac{\sum (X-\chi)^2}{n} \right]^{0.5}$$

$$NME = \frac{100}{n} \qquad \sum \left[\frac{ABS(X-\chi)}{X} \right]$$

where: X = Observed value (zero for charge balance)
χ = Estimated value
n = Number of samples

RMSE is in the units of X; NME is a percentage value.

To facilitate error analysis, the dates with significant deviations between measured and predicted sum of constitutents, specific conductance, and charge balance (assuming the normal charge balance is zero) are also listed with the error table. Data for these dates can be checked by comparison with USGS Water Supply Papers. If specific errors are not found, unreasonable values may be set to zero and new values will be estimated by the program. If changes are made, steps 3, 4, and 5 must be reprocessed.

QWTAB2 requires that site-specific data be initialized in the program. These data include the TDS regression coefficients and the conductance constant (α) from step 3, and the log-log conductance versus flow regression slope from step 4. Two dates are also required, the beginning of specific conductance monitoring and the beginning of flow regulation by an upstream dam. The former is determined by the first date of daily specific conductance under statistic code 3. Flow regulation dates are generally given under "Remarks" in the station description in Water Supply Papers.

Site-specific values are set using XEDIT. The source code must then be replaced to save the edited values. The program is run by submitting procedure file RQWT2. This must also be edited to read the desired input and to specify output file names for both the data and error analysis tables.

The data and error files in disk storage may be printed on the line printer or Xerox. The error file may then be purged, but the data file must be preserved, because it is input to the monthly values generation program in step 6. After final data corrections, the WATSTORE water quality data file is no longer needed and may be purged or archived.

Step 6 — Monthly Value Generation

Program QWMON uses results from the previous five steps to generate the mean monthly values for streamflow, conductance, and solute concentrations. These are computed from data in the three WATSTORE data files and previous estimates for missing values. The program is divided into three parts: (1) compilation of daily data, (2) estimation of missing values between samples, and (3) computation of monthly means.

Compilation of daily data. — QWMON first assembles data from three sources into a single daily values file. The sources are the two WATSTORE daily values files for streamflow and specific conductance, and the QWTAB2 output which includes WATSTORE water quality data and estimates for missing values within samples. This part of the program simply increments the Julian date (based on a 366-day calendar) and assigns to a scratch file the proper daily values for flow, conductance, solute concentrations, and sum of six ions. Previously estimated values are flagged. If an analysis is incomplete and the sum of six ions cannot be computed, the estimate using residue TDS will be used and flagged. Missing values for streamflow are labeled "-1" to differentiate them from true zero flow values. Water quality analyses for composite samples are assigned to each day within the composite period. Discrete sample analyses are assigned only to the day the sample was collected.

Estimation of missing values. — Following initial compilation, missing daily values are filled in by weighted linear interpolation, as described in the body of this report. The actual mechanics of estimating missing values involves creating a partial array of the data and computing values where zeros or -1's (for streamflow) occur. Array element numbers, rather than Julian dates, define the interpolation period to avoid problems with interpolating over New Year's Day or February 29. The array is sized so that all missing values in the first 61 elements will be estimated if sufficient data are available. To ensure this, 81 additional elements must be included, making an array of 142 elements. This sizing depends on the selection of maximum interpolation intervals, as defined below. After completion of the computational loop, the first 60 elements are written to a scratch tape;

STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH

IN THE RELATIONSHIP SC=K*Q**B, B = -.59
DATE CONTINUOUS EC MONITORING BEGAN = 0
DATE FLOW REGULATION BEGAN = 0

WATER QUALITY DATA FILE TABULATION
(VALUES IN MG/L UNLESS OTHERWISE SPECIFIED)

DATE(S)	CALCIUM	MAGNESIUM	SODIUM	CHLORIDE	SULFATE	BICARB.	DISSOLVED SOLIDS RESIDUE	DISSOLVED SOLIDS CALC'D	SP COND (US/CM) OBS	SP COND (US/CM) PRED	NET CHARGE (MEQ/L)
281001 - 281010	163.0	72.0	226.0	133.0	794.0	209.0	0.0	1597.0	0.0	2115.6	.182
281011 - 281020	171.0	69.0	204.0	106.0	778.0	216.0	0.0	1544.0	0.0	2044.8	.357
281021 - 281031	138.0	64.0	194.0	114.0	661.0	213.0	0.0	1384 0	0.0	1873.3	.123
281101 - 281110	143.0	67.0	200.0	100.0	721.0	210.0	0.0	1441.0	0.0	1925.8	.076
281111 - 281120	123.0	61.0	181.0	108.0	594.0	214.0	0.0	1281.0	0.0	1752.0	.110
281121 - 281129	124.0	62.0	196.0	122.0	595.0	224.0	0.0	1323.0	0.0	1800.3	.315
281201 - 281210	125.0	64.0	211.0	144.0	608.0	222.0	.0.0	1374.0	0.0	1869.6	.324
281211 - 281214	142.0	73.0	233.0	168.0	681.0	253.0	0.0	1550.0	0.0	2062.8	.165
281219 - 281220	142.0	73.0	233.0	168.0	681.0	253.0	0.0	1550.0	0.0	2062.8	.165
281221 - 281231	143.0	73.0	240.0	189.0	668.0	262.0	0.0	1575.0	0.0	2094.9	.050
290101 - 290110	126.0	62.0	214.0	159.0	586.0	231.0	0.0	1378.0	0.0	1875.5	.227
290111 - 290120	123.0	61.0	202.0	156.0	550.0	231.0	0.0	1323.0	0.0	1815.6	.307
290121 - 290130	116.0	59.0	195.0	141.0	535.0	219.0	0.0	1265.0	0.0	1746.3	.421
290201 - 290210	117.0	58.0	196.0	135.0	552.0	212.0	0.0	1270.0	0.0	1750.7	.362
290211 - 290219	140.0	66.0	219.0	164.0	607.0	268.0	0.0	1464.0	0.0	1958.9	.288
290220 - 290228	118.0	48.0	160.0	110.0	509.0	182.0	0.0	1127.0	0.0	1588.9	.115
290301 - 290310	118.0	52.0	172.0	105.0	544.0	195.0	0.0	1186.0	0.0	1646.1	.166
290311 - 290320	113.0	56.0	190.0	121.0	542.0	214.0	0.0	1236.0	0.0	1699.7	.307
290321 - 290331	111.0	50.0	173.0	103.0	518.0	207.0	0.0	1162.0	0.0	1604.3	.096
290401 - 290410	82.0	32.0	101.0	67.0	297.0	171.0	0.0	750.0	0.0	1088.3	.243
290411 - 290420	73.0	29.0	83.0	59.0	246.0	178.0	0.0	668.0	0.0	963.6	-.063
290421 - 290430	63.0	24.0	64.0	40.0	189.0	157.0	0.0	537.0	0.0	782.8	.267
290501 - 290510	57.0	21.0	39.0	29.0	149.0	166.0	0.0	461.0	0.0	652.3	-.372
290511 - 290520	41.0	13.0	25.0	13.0	81.0	129.0	0.0	302.0	0.0	423.1	.036
290522 - 290531	40.0	11.0	23.0	10.0	76.0	114.0	0.0	274.0	0.0	389.4	.169
290601 - 290610	39.0	12.0	17.0	10.0	65.0	119.0	0.0	262.0	0.0	366.7	.088
290611 - 290613	40.0	10.0	16.0	12.0	68.0	100.0	0.0	246.0	0.0	358.3	.122
290617 - 290620	40.0	10.0	16.0	12.0	68.0	100.0	0.0	246.0	0.0	358.3	.122
290621 - 290630	36.0	12.0	21.0	15.0	82.0	99.0	0.0	265.0	0.0	390.7	-.055
290701 - 290710	48.0	16.0	35.0	28.0	125.0	112.0	0.0	364.0	0.0	548.0	.007
290711 - 290713	67.0	23.0	63.0	43.0	213.0	138.0	0.0	547.0	0.0	813.2	.067
290715 - 290717	67.0	23.0	63.0	43.0	213.0	138.0	0.0	547.0	0.0	813.2	.067
290719 - 0	67.0	23.0	63.0	43.0	213.0	138.0	0.0	547.0	0.0	813.2	.067
290722 - 290731	83.0	27.0	69.0	38.0	278.0	155.0	0.0	650.0	0.0	946.6	-.035
290801 - 290802	92.0	31.0	60.0	32.0	311.0	151.0	0.0	677.0	0.0	989.4	-.100
290804 - 290810	92.0	31.0	60.0	32.0	311.0	151.0	0 0	677.0	0.0	989.4	-.100
290811 - 290820	91.0	35.0	80.0	54.0	329.0	157.0	0.0	746.0	0 0	1093.8	-.045
290821 - 290831	97.0	46.0	107.0	80.0	420.0	171.0	0.0	921.0	0.0	1329.6	-.523
290901 - 290910	120.0	45.0	119.0	54.0	477.0	181.0	0.0	996.0	0.0	1404.1	.447
290911 - 290920	74.0	32.0	71.0	41.0	268.0	152.0	0.0	638.0	0.0	939.1	.187
290921 - 290930	85.0	31.0	81.0	47.0	304.0	162.0	0.0	710.0	0.0	1031.5	.006
291001 - 291003	82.0	38.0	98.0	61.0	340.0	160.0	0.0	779.0	0.0	1136.5	.060
291005 - 291010	82.0	38.0	98.0	61.0	340.0	160.0	0.0	779.0	0.0	1136.5	.060
291011 - 291015	90.0	39.0	103.0	62.0	364.0	167.0	0.0	825.0	0.0	1194.5	.117

Figure A-5. — Partial data table output from program QWTAB2.

ESTIMATED VALUE ERROR TABULATION

STATION 9180500 - COLORADO RIVER NEAR CISCO UTAH

PARAMETER	NUMBER OF OBSERVATIONS	MEAN VALUES (OBS)	(PRED)	ERRORS MAXIMUM (VALUE)	(DATE)	NORMALIZED MEAN (PERCENT)	ROOT-MEAN-SQUARE
TDS (MG/L)	858	1037.7	1037.7	239.2	650914	2.0	28.2
SPECIFIC CON (US/CM)	1011	1445.3	1458.8	644.0	651105	4.0	74.9
NET CHARGE (MEQ/L)	1300	.060	0.0	1.279	780419	.6	.245

ALPHA = 6.28 BETA1 = -13.87 BETA2 = .97559

DIFFERENCE BETWEEN OBSERVED AND PREDICTED VALUES
(* = SIGNIFICANT AT 95% LEVEL OF CONFIDENCE)

DATE	NET CHARGE (MEQ/L)		DISSOLVED SOLIDS (MG/L)		SPECIFIC COND (US/CM)
290821	-.523	*	0.0		0.0
301021	.605	*	0.0		0.0
301101	.577	*	0.0		0.0
301111	.669	*	0.0		0.0
301211	.481	*	0.0		0.0
310101	.515	*	0.0		0.0
310105	.515	*	0.0		0.0
310111	.512	*	0.0		0.0
310221	.517	*	0.0		0.0
330821	.593	*	0.0		0.0
340111	.499	*	0.0		0.0
340721	.565	*	0.0		0.0
340801	.606	*	0.0		0.0
340811	.521	*	0.0		0.0
340911	.553	*	0.0		0.0
381011	-.020		-58.4	*	-82.8
381021	-.022		-61.0	*	-60.9
501012	-.346		-55.8	*	-17.7
501017	-.346		-55.8	*	-17.7
501021	-.038		-56.7	*	3.7
501101	.067		-74.4	*	43.2
501201	-.665	*	-44.5		-44.3
501211	-.703	*	-40.5		-44.4
510210	-.531	*	-19.2		18.7
510220	-.708	*	-7.4		-20.7
510321	-.488	*	-28.0		22.6
510901	.481	*	-32.8		-97.3
510921	.550	*	-41.5		-78.4
511021	-.572	*	-29.9		-95.4
521021	.330		55.9	*	-28.9
521101	.239		-59.7	*	-22.5
530920	.594	*	-103.3	*	-5.3
531001	.538	*	24.5		13.1
531009	.538	*	24.5		13.1

Figure A-6. — Example of error statistics table from program QWTAB2.

indexes (k) on the remaining 82 elements are redefined to k-60; and the next 82 daily values are read into the bottom of the array.

Computation of monthly means. — Measured and estimated daily values are then used to compute the mean monthly streamflow (m^3/s) and solute concentrations (mg/L). Output is written to TAPE7 and stored on a user-specified disk file.

To aid in judging the quality of the generated data, a second output file is written, which tabulates the percentage of days with estimated values for each month and each parameter. Monthly mean solute concentrations based on a high percentage of estimates may be inaccurate, especially when much of the conductance data are also estimated. This may be justification for the exclusion of data points identified as outliers in later analyses.

Operating procedure. — QWMON is run in BATCH mode by submitting a procedure file, RQWMON. Prior to submittal, the following lines must be edited as indicated, to access the desired input files and to specify the output file names.

```
GET, TAPE1 = Output from QWTAB2,
     TAPE2 = streamflow data,
     TAPE3 = conductance data
1, CALL, SAVER(I=TAPE6,J=estimate table
                file name)
CALL, SAVER(I=TAPE7,J=output data file
                name)
```

In addition to the monthly means and percentage estimates tables, this procedure produces an output file, OQWM, which includes messages written during program execution, run cost data, and a complete dayfile.

Step 7 — Plotting Monthly Values

Generated monthly data are plotted to check for reasonable relative values. Program PLTWQM plots streamflow and solute concentration values from QWMON output and uses flow and concentration to compute and plot the solute load (kg/s). Because plots are made on 10-year intervals, several plots may be needed to display the historical record for any single parameter. The cations and anions are grouped on common plots to show relative values. Monthly data points are connected for sequential months. Possible errors may be determined visually and checked in intermediate output tables.

The program is run using a BATCH submittal procedure, RPLTQWM. The following lines must be edited for the specification of input and output file names.

```
GET, PLTWQM, input file name
LGO, input file name, OPL
1, CALL, SAVER(I=PLFILE, J=plot output file
                name)
REPLACE, OPL=message file name
```

The input file is a monthly data table (TAPE7 output) from QWMON.

The procedure is run by the interactive commands:

```
GET, RPLTQWM
(edit)
SUB
```

The plot output contains data used to generate plots using a DISSPLA post-processor procedure, such as COMP80 or TEKTRON. The message file contains execution information generated by the DISSPLA graphics package, run cost data, and a complete dayfile. It should be checked prior to generating hardcopy plots.

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The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

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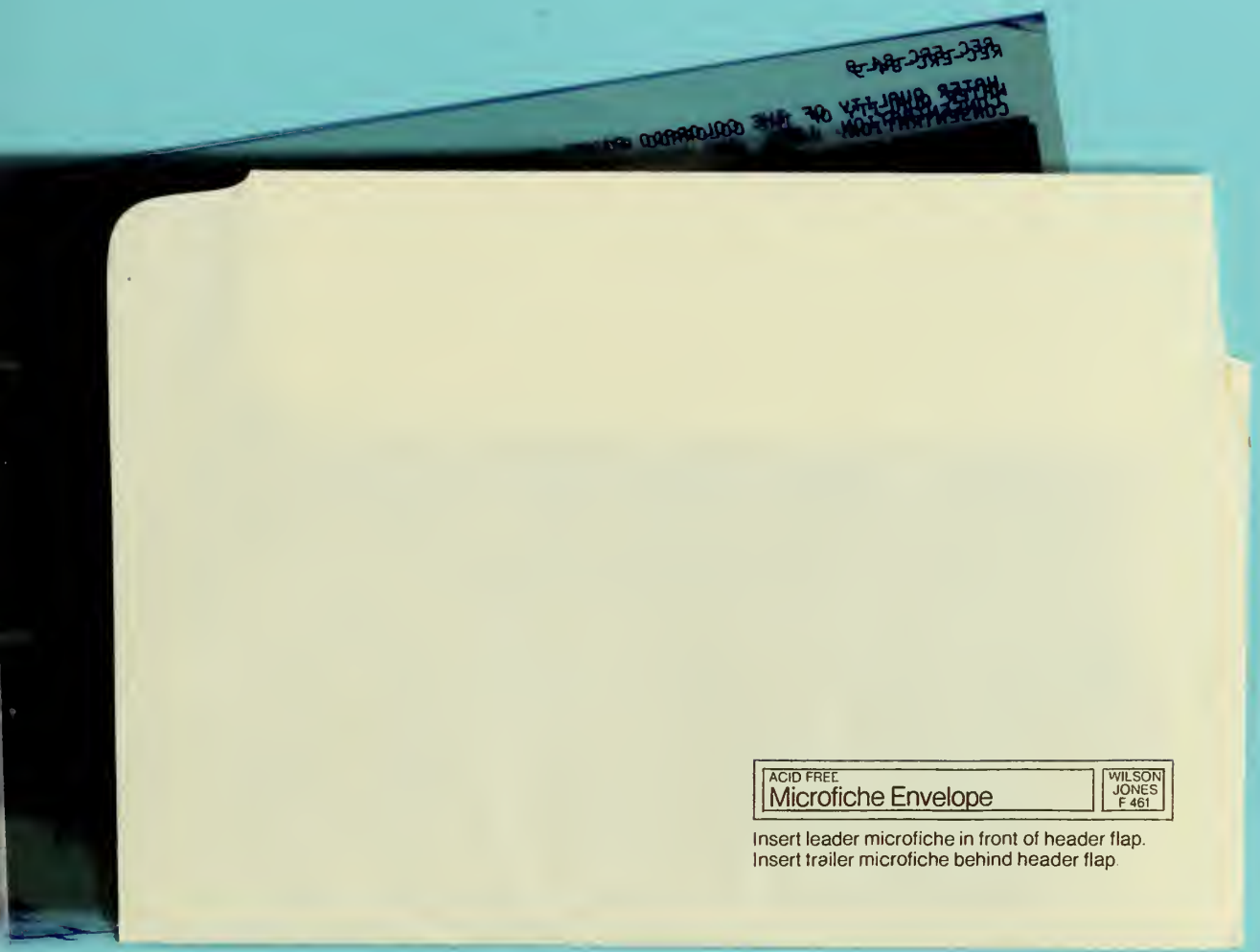

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